X-RAY STUDIES ON 2:6-DIHYDROXY BENZOIC ACID AND ITS SALTS

THESIS

PRESENTED FOR THE DEGREE OF

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P R E F A C E

This thesis describes research work carried out during a three-year period, commencing 1950, in the Chemistry Department of the University of Glasgow. Some modifications were made in 1958.

I wish to express my gratitude to my supervisors, Professor J.M. Robertson and Dr. J.C. Speakman, for suggesting the topics of research and for their constant guidance and encouragement. I should also like to thank Dr. J. Reid of the Gardiner Institute of Medicine, University of Glasgow for supplying samples of sodium 2:6-dihydroxy benzoate and 2:6-dihydroxy benzoic acid and for his helpful discussion.

In conclusion, I am indebted to the Department of Scientific and Industrial Research for a maintenance allowance.

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SUMMARY

This thesis describes an investigation of 2:6-dihydroxy benzoic acid and its salts by X-ray analysis. The unit cell dimensions of 2:6-dihydroxy benzoic acid monohydrate have been obtained and the possible space group is discussed. The main part of the work is concerned with the crystal and molecular structure of the potassium and rubidium salts of 2:6-dihydroxy benzoic acid and a complete structure analysis of the potassium salt has been carried out.

The crystals of 2:6-dihydroxy benzoic acid monohydrate are orthorhombic, space group $Pna2_1$ (C_{2v}^9) or $Pnma$ (D_{2h}^{16}) with 4 molecules per unit cell. The unit cell dimensions are $a = 6.77$, $b = 9.67$ and $c = 11.92$ Å.

Potassium 2:6-dihydroxy benzoate crystallises in the monoclinic space group $P2_1/n$ (C_{2h}^5) with four molecules per unit cell. The unit cell dimensions are $a = 3.94$, $b = 15.10$ and $c = 13.37$ Å. $\beta = 99^\circ 11'$ The structure of the compound has been elucidated by the Isomorphous Replacement method, in which use was made of the isomorphous rubidium salt. Refinement proceeded from a study of Fourier syntheses in all three zones and Fourier difference syntheses projecting on (100). Electron density projections on the (100) plane gave good resolution of all the atoms in the asymmetric unit. The shortness of the a axis prevented good resolution in the h0l and hk0 zones and the x co-ordinates were obtained largely by trial and error methods after an approximate x co-ordinate for the potassium ion had been obtained from a study of the far-out reflections in the hk0 and h0l zones. However, from the electron density projections, x co-ordinates could be assigned to the potassium ion and most of the oxygen atoms. The co-ordinate standard deviations are less than .02 Å.

The molecule is planar within experimental error and bond lengths vary between 2.75 and 3.03 Å for potassium-oxygen bonds, between 1.25 and

1.40 Å for carbon-oxygen bonds and between 1.39 and 1.53 Å for carbon-carbon bonds. There are two intramolecular hydrogen bonds joining the oxygen atoms of the carboxyl group to the phenolic oxygens; these are 2.50 and 2.56 Å in length.

There are no discrete molecules and the packing is determined by the co-ordination of the organic residues to a central metal ion by potassium-oxygen links in all directions, involving both phenolic and carboxylic oxygens. The potassium is surrounded by seven bonded oxygens, six of which are arranged to form a trigonal prism. The ion shows a preferential attraction to one of the two oxygen atoms of the carboxyl group and has an attraction of similar magnitude to both of the phenolic oxygens.

The bond lengths within the organic residue are reasonably consistent with Cochran's values for salicylic acid.

It is expected that the work on the potassium salt will shortly be published.

Introduction

(a) General

This work was undertaken subsequent to medical research done in the Gardiner Institute of Medicine, University of Glasgow.[1] At a time when cortisone was prohibitively expensive attempts were made to find a drug of similar therapeutic action on rheumatic diseases which would be cheaper and, if possible, safer than cortisone.

The structure of the complex molecule cortisone was not known, but as with so many effective drugs, it began to be used not for biochemical but for empirical reasons. Many medicinal herbs and roots which are chemically very different, sometimes to the extent of containing different elements, show similar curative properties which, one then suspects, may be due to one or more chemical groups recurring in the various molecules, or perhaps even to inter- or intra-molecular forces. It is economically unsound to manufacture and unwise to administer a drug consisting to a large extent of unnecessary and perhaps even undesirable chemical groups. Knowledge of the 'common factors' might well help to reduce the vast array of drugs on the market by permitting the synthesis of a limited number of smaller and cheaper molecules which would be equally effective.

Many drugs have been used in the treatment of rheumatic diseases. Sodium salicylate has long been established in the treatment of rheumatic fever but is not ideal, as the dose required for full therapeutic action often gives rise to undesirable side effects. After cortisone was discovered attention was again turned to sodium salicylate and some related compounds; medical and chemical evidence suggested that the desired curative properties increased according to the chelation in the molecule. The most promising compound was sodium γ-resorcylate or sodium 2:6-dihydroxy benzoate, and in order to prove the chelation theory an X-ray analysis seemed the obvious thing to do.

From the structural aspect the problem was an interesting one, partly because the structure of salicylic acid was then in process of solution, and also because of the interest in this department in salts and the solution of their structures by the Isomorphous Replacement method and Patterson techniques.[2,3,4,5]

(b) Intermolecular Forces

In organic crystal structures the two dominant factors governing the association of neighbouring molecules, are the van der Waals force of attraction and the hydrogen bond; it would appear that, in those organic substances connected with body chemistry, the latter may well be the more significant. This is a reasonable assumption, because the hydrogen bond is at once stronger than the van der Waals force - strong enough to retain certain substances to their nature configurations within the body - and yet so much weaker than the covalent bond, having an energy of formation of only $\sim$ 5 K cals/mole, that it lends itself to ready formation and rupture in processes taking place at body temperature. It has been realised that many complex and heretofore inexplicable physiological phenomena may be accounted for by hydrogen bond formation and resonance: together, these two factors confer directional properties along with the power of transmission, and Pauling[6] has forecast that they may prove to play an important role in the transmission of impulses along nerves and in the brain; in 1951 Pauling and Corey[7,8] suggested that the contraction of muscle may be due to the rupture of intermolecular hydrogen bonds although there was no direct evidence to bear out this theory.

(c) The Biological Importance of the Hydrogen Bond.

Physical chemists have been showing that more and more compounds of biological importance have an abundance of hydrogen bonds. For example, Cochran and Penfold[9] have proved that l-glutamine, an essential compound in many metabolic processes, has five hydrogen bonds, each linking a nitrogen and an oxygen. In no field have such discoveries been more

striking than in that of the proteins, whose complicated structures are now known to depend for their very existence and stability on the directional characteristics of the N-H---O bond. As far back as 1936 Mirsky and Pauling[10] suggested that the denaturation of proteins might be due to the rupture of hydrogen bonds. The protein molecules are both large and complicated, and their structural details are still the subject of much speculation. Although no precise structures are known as yet, the vast numbers of possible structures have been limited by a very few simple rules, the most important being the approximate collinearity of the N-H---O bond, the planarity of the amide group, and the concept of maximum hydrogen bonding.[11]

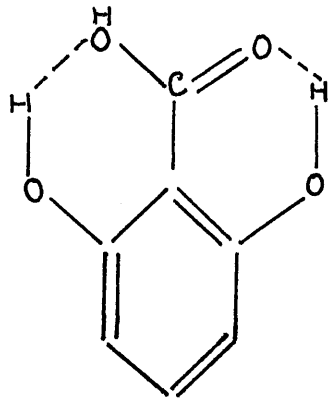
Considerable help to the understanding of the protein structures has been given by the preparation and study of the synthetic polypeptides, which, apart from polyglycine[12,13] are well known to exist in two forms, the α, or helical form, and the β, extended form. The α-helix is conditioned by intra-molecular hydrogen bonds linking each amide group to the third along the spiral whereas in the β form, hydrogen bonding is between neighbouring chains and completely intermolecular.[14] These α and β polypeptides are reversibly interconvertible[15,16,17] and contraction of β to α can be supposed to involve the rupture of inter-molecular hydrogen bonds, with the subsequent formation of intra-molecular hydrogen bonds and vice versa. Both forms are closely related to the natural configurations of the keratin, myosin, epidermin, fibrinogen group of fibrous proteins, although here the molecules are rather more complicated and tend to be cabled together, e.g. frog sartorius muscle is compounded of both myosin and actin.[18] For the other sub-group of the fibrous proteins, the collagen-gelatin group, Pauling and Corey have postulated a molecular structure of three polypeptide chains intertwined and held together by lateral hydrogen bonds; this is still substantially undisputed.[19] Similarly, the corpuscular proteins would appear to be composed of folded polypeptide chains[20,21]. In all cases the polypeptide chains assume the configurations which make maximum use of their hydrogen bonding capacities, and their molecular arrangement is largely determined by the dimensions

and directional characteristics of the N-H---O bonds.

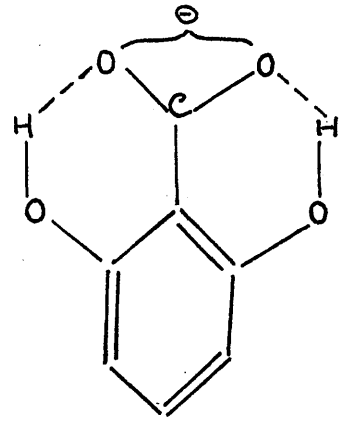
In view of the widespread interest in associating changes in physical, chemical and biological properties with changes in the complexion of forces such as the hydrogen bond it is reasonable to examine the anti-rheumatic drugs from this standpoint.

(d) The Possible Significance of the Hydrogen Bond in Anti-Rheumatic and Anti-Diabetic Drugs.

Reid, Watson, Cochran and Sproull[11] commenced their search for a new anti-rheumatic drug by studying the therapeutic action on rheumatic fever of m- and p-hydroxy sodium benzoate and found them to be quite inactive. This striking difference between the ortho-, and the meta- and para-isomers at once suggested an ortho effect, and the possibility that the therapeutic action of sodium salicylate might be due to chelation or internal hydrogen bond formation. An accumulation of indirect evidence from spectroscopic and solubility measurements, measurements of dissociation constants, heats of vaporisation etc., on salicylic acid and some related compounds made it reasonable to assume chelation in these compounds. Cochran[22] has since produced direct quantitative evidence of chelation in salicylic acid by doing a careful X-ray structure analysis in which the hydrogen atoms were located. If the therapeutic and pharmacological effects of the salicylate ion are due to chelation, these could be enhanced by increased chelation, which might be induced by introducing a second ortho-hydroxyl group into salicylic acid to give γ-resorcylic acid, and thence the γ-resorcylate ion. One might reasonably expect that these molecules could be written as I - the acid[6] and II - the anion, as follows.



(I)



(II)

The effect of sodium γ-resorcylate on healthy individuals has been studied and described in the British Medical Journal.[1] It has been found that a dose of sodium γ-resorcylate has the same action on rheumatic fever as ten times that dose of sodium salicylate, but produces side effects much more readily than much larger doses of sodium salicylate. Its advantages, therefore, are rather diminished by the fact that the beneficial and undesirable effects are equally potentiated, and that the lethal dose of sodium γ-resorcylate is less than that of sodium salicylate. The therapeutic and pharmacological effects of certain other compounds related to sodium salicylate have also been tested: sodium benzoate and sodium m- and p-hydroxy benzoate have no effect at all; sodium 2:5-dihydroxy benzoate, as one would expect, has the same effect as sodium salicylate, and sodium γ-resorcylate and cortisone are ten times more effective.[1,23] All these results are in agreement with the proposed mechanism of chelation.

Recently, the effect of aspirin on diabetes mellitus was reconsidered[24] and subsequently evidence on the effect of related drugs including salicylate and γ-resorcylate has been compiled.[25] Again, the strength increases with the potential intra-molecular hydrogen bonding. Of considerable interest and very relevant to this discussion is the fact that 2:4-dinitrophenol is very similar clinically and biologically to salicylate[26] and this would most certainly bear out any theory of chelation.

There are however certain differences in the effect of the last two drugs which suggest that they are neither identical nor independent in action,[26,27,28] and there can be no definite medical evidence that the anti-rheumatic and anti-diabetic effects increase directly with intra-molecular hydrogen bonding. It can be said, from clinical and biological evidence, that sodium salicylate is a powerful metabolic stimulant and increases oxygen consumption[29] and inhibits oxidative phosphorylation[30], but until the chemical nature of these actions and the mode of attachment to protein in the body is established, it is impossible from the medical aspect to prove definitely that chelation, far less increased chelation, is the operative factor.

Structural investigations however have shown the presence of intra-molecular hydrogen bonding in salicylic acid[22], (and by inference in the anion) and can be used to indicate any increase in hydrogen bonding in γ-resorcylic acid and its salts.

(e) The Nature of the Hydrogen Bond

One of the earliest references to the hydrogen bond was made by Moore and Winmill[31] who, when studying the state of amines in aqueous solution, postulated a bond involving di-valent hydrogen to account for the weakness of alkyl ammonium hydroxides relative to the quaternary alkyl ammonium hydroxides. Pfeiffer[32], working on organic compounds, used a similar concept to explain the low reactivity of hydroxyl ortho to carbonyl, as compared with hydroxyl meta to carbonyl.

These were vague qualitative theories however and the first postulate of the mechanism of hydrogen bond formation was made by Latimer and Rodebush[33]. These authors were investigating the relation between certain associated liquids and their abnormally high dielectric constants, and the fact that such liquids generally contained hydrogen. They had assumed that the association was due to the attraction between two opposite dipoles, an assumption which however could not account for the low dielectric constant of HCl compared to H_2O and HF. In terms of the Lewis valency concepts, they then postulated that the free pair of

electrons on one water molecule might exert a sufficient force on a hydrogen atom, held by a pair of electrons on yet another water molecule. Continuous polymerisation could thus take place and the hydrogens held by two oxygen octets would form weak bonds capable of considerable displacement by an electric field, so that a high dielectric constant would result.

This theory, although correct in implying two bonds from the hydrogen atom, is wrong in implying two covalent bonds, as it has since been pointed out by Pauling[34] that the hydrogen atom with only one stable orbital (1S) available for bond formation can involve no more than one purely covalent bond, and it is now generally agreed that the hydrogen bond involves the proton and two strongly electronegative atoms, the strength of the bond increasing with the electronegativity of the atoms. Thus the F-H----F bond is stronger than the O-H----O bond. The low dielectric constant of HCl is due to the fact that although chlorine is strongly electronegative, the size of the chlorine ion considerably reduces its electrostatic attraction. Once the proton has attracted two electronegative atoms, steric hindrance prevents further attraction. The limitation of such bonds to hydrogen can be explained very easily by the anomalous nature of hydrogen which forms a cation with no inner shell of electrons. It therefore has a powerful force of attraction and is capable of close approach to an anion without steric interference.

The question arises as to whether or not the proton is located nearer one anion than the other, in other words, is the hydrogen bond symmetrical or asymmetrical? The only really convincing evidence for a symmetrical hydrogen bond is the thermodynamic and spectral data put forward by Westrum and Pitzer[35] for the KHF_2 molecule which indicates a single potential minimum midway between the fluorine ions, at which the hydrogen must be situated. The O-H----O bonds in potassium hydrogen bisphenyl acetate[2], potassium hydrogen di-p-hydroxybenzoate hydrate[3] and potassium hydrogen dibenzoate[4] demand a symmetrically placed proton as the bond crosses a centre of symmetry. This symmetrical effect could be a statistical one created by the proton vibrating between two

equilibrium positions equidistant from the centre of symmetry, and this is in accordance with the infra-red studies of Davies and Thomas[36] on KH bisphenylacetate.* Bacon and Curry[37] have since carried out a neutron diffraction study of that compound and failed to observe any elongation of the hydrogen peak along the direction of the bond which might be caused by vibration. Hadzi and Novak[38] believe that here there is indeed a case for a genuine symmetrical O-H----O bond. From the diffraction studies there can be no conclusive evidence as there is a large amount of thermal vibration and the H atom peak is in any case diffuse. Meanwhile, the vibration theory is the only one which satisfies the infra-red and diffraction data.

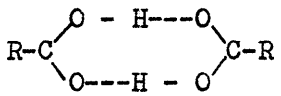
For O-H----O bonds generally, the infra-red data favour an unsymmetrically situated hydrogen[39]. The O-H----O bond varies in length from about 2.5 Å to 2.9 Å and the proton appears to be about 1 Å away from one of the oxygens. One example is that of ice; X-ray evidence[40] indicates an O-H----O bond of 2.76 Å whereas infra-red investigators put forward an OH distance of .99 Å[41]. If the O-H----O bonds in ice were symmetrical there would be no evidence of discrete water molecules and Pauling has shown that the residual entropy of both ice and water forbids a completely uniform structure.[42] He postulates an 'average' structure involving 'half hydrogens'. This has been confirmed by the neutron diffraction study of heavy ice by Peterson and Levy[43] who quote two O-D distances of 1.01 Å and O-½D- ½D-O distances of 2.75 and 2.77 Å.

More recently Peterson and Levy[44] carried out a neutron diffraction study of potassium hydrogen maleate and have produced evidence for at least a statistically symmetrical hydrogen bond. The unusually short intramolecular hydrogen bond length of 2.46 Å reported by Shahat[45] in the study of maleic acid seemed remarkably near to the value of 2.30 Å predicted by Donohue[46] for a symmetrical hydrogen bond. This led Cardwell, Dunitz and Orgel[47] to suggest that when the first proton of the acid was removed in ionisation, the second proton, (in the absence of repulsion from the first proton) could move nearer to the mid-point between the oxygens and might possibly be symmetrically situated. These authors accordingly made an infra-red investigation of potassium hydrogen

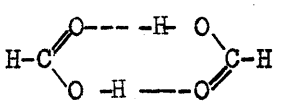
* *Davies and Thomas have since withdrawn their conclusions in an as yet unpublished communication.*

maleate and confirmed that the internal hydrogen bond is indeed stronger. The neutron diffraction evidence demands a symmetrically placed hydrogen, as in the space group Pbcm the maleate ion must have a mirror plane of symmetry. Peterson and Levy[44] have evidence that the oxygen atoms of the carboxyl group undergo considerable vibrational displacement, but not so the proton and, although they cannot prove actual centering, they state that a close approach to it is implied.

Formic and acetic acids form infinite hydrogen bonded chains in the solid state[48,49]; in the liquid state they form dimers associated by hydrogen bonds strong enough to persist even into the gaseous state and this has permitted these compounds to be studied by X-ray, electron diffraction, and spectroscopic methods. For acetic acid in the solid state Jones and Templeton[49] quote an O-H----O distance of 2.61 Å and for the dimer Karle and Brockway[50] quote 2.76 Å. Herman and Hofstadter[51,52], from their infra-red studies on light and heavy acetic acid, find an increase in the C-H and O-D distances from about .97 Å in the monomer, to about 1.07 Å in the dimer. This increase would have to be up to at least 1.3 Å for there to be a symmetrically situated hydrogen in the solid or liquid state. If the proton were midway between the two oxygens, one would suppose the structure of the carboxylic acid dimer to be



X-ray investigations on succinic acid[53,54] show different C-O bond lengths and indicate the structure



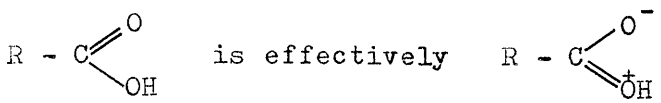
which implies unsymmetrical hydrogen bonding, although it does not indicate to which oxygen the hydrogen is closest. This eliminates Sidgwick's suggestion[55] that there is a resonance structure as follows:

Gillette and Sherman[56] calculated the resonance energy contribution in formic acid dimer and found that resonance could only account for 50% of the total energy required even when the hydrogen atoms are placed in the most favourable positions.

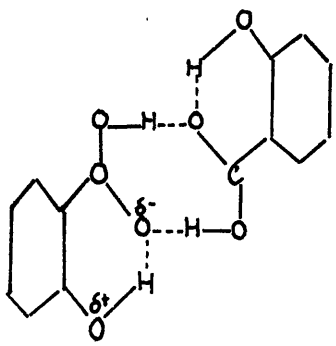
A tautomeric effect may occur however and the proton may oscillate about two equivalent minima in the field of its own potential function. This would then account for a contribution from the two carboxylic acid resonance structures shown, and is in accordance with the potential energy curves of Huggins.[57]

The lengths of the O-H----O bonds reported fall into certain classifications and, as might be expected, depend on the conjugation of the parent system; the greater the conjugation, the greater is the electronegativity of the O atoms and the O-H----O bond becomes shorter, stronger and more stable. Hydrogen bridges involving water are the longest O-H----O bonds reported and the value already quoted for ice is 2.76 Å.[40] The bonds involving the hydroxyl group, e.g. the chelate link in question, are shorter because of the increased electronegativity conferred by a resonating system. An example of an inter-molecular hydrogen bond between hydroxyl oxygens is given by α-resorcinol[58] where hydrogen bonds have been found by X-ray analysis to be 2.66 and 2.75 Å. α-Resorcinol was the first aromatic molecule to be studied by neutron diffraction[59]. Bacon and Curry quote a mean O-H----O bond length of 2.72 Å and an O-H length of 1.02 Å. The O-H----O atoms are not collinear, nor is the hydrogen symmetrically situated.

The intra-molecular hydrogen bond in salicylic acid is 2.59 Å[22]. This is an interesting molecule, as a further type of hydrogen bonding occurs, that involving a carboxyl group, in the salicylic acid dimer. Hydrogen bonds formed by dimerised carboxylic acids are generally shorter and stronger than either of the preceding types owing to the resonance involved.



Here, the oxygen which accepts the proton has an increased negative charge while the proton donator has an increased positive charge, thus enhancing the ionic character of the bond. In salicylic acid this is magnified still further by the stabilising effect of the chelate link in the structure as put forward by Pauling[6].



Spectroscopic evidence for this compound indicates that there are no OH groups which exist unbonded[6]. The actual positions of the hydrogens have been found by Cochran[22] who gives a full account of all the possible resonance structures.

The resonance effect is tending more and more to the complete resonance and stability of the anion. The shortest of the O-H----O bonds generally are those found in acid salts. Hendricks[60] quotes a value of 2.54 Å for KH_2PO_4. Among the shortest of all O-H----O bonds recorded are those of 2.50 Å found in oxalic acid dihydrate[61] and in urea oxalate[46] and 2.46 Å found in maleic acid[45].

As advances in many fields, particularly the biological field, depend largely on the study of hydrogen bonding, many physical methods are directed to this research, all however falling short in some respect. Only in favourable cases is it possible to locate the hydrogens at all.

(f) Some Physical Methods suitable for the Detection and Measurement of the Hydrogen Bond.

Of the physical methods available for the determination of bond lengths the spectroscopic method is the most accurate, but for complete information is confined to gases and vapours and can only be applied to simple molecules. In condensed phases however the quantised nature of the rotational energy levels disappears because of the strong inter-molecular forces and no direct information on individual molecular dimensions can be obtained. However the spectroscopic method is valuable as being a rapid means of finding the direction of hydrogen bonds. In the polypeptides, for example, stretching and deformation frequencies were calculated for NH and CO bonds and, using polarised infra-red to determine the dichroic ratios the presence of hydrogen bonding parallel or perpendicular to the fibre axis could be determined[62].

Diffraction methods are of wider application and can be applied to the gaseous or crystalline state. Electron diffraction methods are confined to gases or solids with high vapour pressure.

Crystal diffraction methods are most useful; these use either sources of neutrons or X-rays. Neutron diffraction is a suitable tool for the location of hydrogen atoms because it is independent of electron distribution and depends only on the nucleus. However it has many disadvantages: these are - the limited resolution obtained because of poor collimation and large specimen, the necessity of having crystals large enough to give adequate intensities and the consequent effects of secondary extinction, the unsuitability of photographic methods for accurate work, and of course the fact that neutron sources are not readily available.

X-ray crystal diffraction has the widest application and is best suited for the complex structures being investigated today; it has the enormous advantage that the complete chemical structure need not be known as instanced by the solution of vitamin B_{12}[63], penicillin[64], and, in

this department, caryophyllene hydrochloride[65]. A survey of the history of X-ray crystallography is given by Robertson[66].

In favourable cases (e.g. naphthalene[67], anthracene[68] and succinic acid[53,54]) hydrogen atoms can be located. Cochran has shown up the hydrogen atoms in adenine hydrochloride[69] and in salicylic acid[22] using Geiger counter methods and by a beautiful structural analysis.

In general, however, hydrogen atoms are not located and bond lengths involving hydrogen are not determined. The method gives a precise knowledge of the positions and spatial arrangements of all other atoms including inter- and intra-molecular distances and hydrogen bonding can of course be inferred from undue shortening of bond lengths: moreover it provides a sound quantitative basis on which infra-red and other more indirect data may be built up unambiguously.

CRYSTAL STRUCTURE ANALYSIS

(a) General.

Single crystal structure analysis consists largely of trial and error and can be a very lengthy process. Although it may be possible to deduce the structure of inorganic crystals directly from the intensities of the reflections on an X-ray diffraction photograph, along with space group considerations, this is not generally the case. For any known structure it is possible to calculate the intensities of the reflections which would be produced, but the reverse is not true. The intensities of the reflections can be related to structure amplitudes, $|F|$ which measure the amplitude of each diffracted wave relative to that produced by one electron at the origin of the unit cell.

$$F(hkl) = \sum_{o}^{n} f_j \exp 2\pi i \, (hx_j/a + ky_j/b + lz_j/c)$$

a, b and c are the lattice parameters, x, y anx z are atomic co-ordinates and h, k and l are Miller indices.

This is a complex quantity characterised by an amplitude, $|F|$, and a phase constant, α, and is the structure factor for the plane (hkl). In the photographic recording of these intensities the phase of the wave is lost and only the amplitude is recorded.

The main problem of X-ray analysis is to allocate the appropriate phase to as many reflections as possible, until an accurate electron density distribution can be evaluated.

The solution generally proceeds by successive approximation using Fourier methods. As the crystal lattice is periodic in three dimensions the electron density can be calculated using a triple Fourier series

$$\rho(xyz) = \sum_{-\infty}^{+\infty}\sum\sum\left\{F(hkl)/V\right\} \exp\left\{-2\pi i\,(hx/a + ky/b + lz/c)\right\}$$

$\rho(xyz)$ $\rho(xyz) = \sum_{-\infty}^{+\infty}\sum\sum\left\{F(hkl)/V\right\} \exp\left\{-2\pi i\,(hx/a + ky/b + lz/c)\right\}$ series is summed over all points;

V is the volume of the unit cell.

For purposes of summation this equqtion can be simplified

$$\rho(xyz) = \sum_{-\infty}^{+\infty}\sum\sum\left\{|F(hkl)|/V\right\} \cos\left[2\pi hx/a + 2\pi ky/b + 2\pi lz/c - \alpha(hkl)\right]$$

Apart from the calculation difficulties the collection of data for a three dimensional synthesis is a formidable task and sufficient information is often obtained from two or more electron density projections, particularly when the molecule is planar and there is likely to be less trouble from overlapping. One great advantage of doing two dimensional summations is that the data can be collected on one Weissenberg film and relative intensities are more easily estimated. The expression for the electron density in projection is further simplified if the crystal has a centre of symmetry, and that centre of symmetry is chosen as the origin, for then the phase angle is either o or π

$$\rho(yz) = \sum_{-\infty}^{+\infty}\sum \pm \left[F(0kl)/A\right] \cos 2\pi(ky/b + lz/c)$$

Different expressions can then be worked out for particular space groups e.g. for $P2_1/n$ as defined later

$$\rho(yz) = 1/A[F(000) + 2\sum_{2}^{\infty}{}^{k=2n} kF(0k0)\cos 2\pi(ky/b) + 2\sum_{2}^{\infty}{}^{l=2n} lF(00l)\cos 2\pi(lz/c)$$

$$+ 2\sum_{1}^{\infty}{}_{1}^{\infty}{}^{k+l=2n} [F(0kl)\cos 2\pi(ky/b + lz/c) + \cos 2\pi(ky/b - lz/c)$$

$$+ F(0kl)\cos 2\pi(ky/b + lz/c) - \cos 2\pi(ky/b - lz/c)]$$

(b) The Patterson Function.

In order to make the maximum use of the X-ray intensity data without any knowledge of phases, Patterson[70] has developed a method involving the squares of the structure amplitudes. He defines the function

$$P(uvw) = (1/V)\int_0^a\int_0^b\int_0^c \rho(xyz)\,\rho(x+u, y+v, z+w)\,dxdydz$$

and its Fourier representation

$$P(uvw) = (1/V^2)\sum_{-\infty}^{+\infty}\sum\sum |F(hkl)|^2 \exp[-2\pi i(hu/a + kv/b + lw/c)]$$

This is analagous to the Fourier expression for an electron density distribution, but instead of giving actual atomic positions this gives a vector representation of the crystal structure with the superposition of inter-atomic distances. The parameters u, v and w represent the displacement of the function $\rho(x, y, z)$ from the point (xyz).

As the Patterson coefficients are all positive the calculation of the Patterson function is simpler than the calculation of the electron density distribution. It may also be possible to sum over a smaller volume of the unit cell because of the increased symmetry of the Patterson function and, in the case of a non-centred crystal, there is the advantage that the Patterson function has a centre of symmetry.

In the evaluation of the electron density distribution only the structure factors of known phase may be used as Fourier coefficients, but in the calculation of the Patterson function all of the available data are used.

(c) The "Sharpened" Patterson.

When the function

$$P(uvw) = 1/V \int_0^a \int_0^b \int_0^c \rho(xyz)\, \rho(x+u,\ y+v,\ z+w)\, dxdydz$$

is summed for point atoms it should have zero value except when x, y, z and x + u, y + v and z + w are atomic positions. In fact there is a distribution of electrons around each atomic position so that the product is rarely zero and the Patterson map becomes more difficult to interpret owing to the poor resolution of the main peaks.

In order to "sharpen" the peaks to approximate to those which would be given by point atoms Patterson suggested using a modified structure factor F_m [71]

$$|F_m|^2 = \left\{ \sum_{j=1}^{N} Z_j^2 \Big/ \sum_{j=1}^{N} f_{oj}^{\,2} \right\} \times |F|^2$$

(where Z_j is the atomic number of the j^{th} atom and f_{oj} is the theoretical atomic scattering factor for that atom).

Patterson successfully used this method to solve the structure of $CuSO_4.5H_2O$.

In the extreme, if f_j is substituted for f_{oj}

$|F_m|^2 = |F|^2 / \hat{f}^2$ (where $\hat{f}$ is a modified unitary scattering factor).

This treatment obviously produces a non-convergent series and for preference one would use a more modified form. However, one ought also to have accurate intensity measurements on an absolute scale. [In this investigation the purpose of the method was to locate the heavy ion, and the latter approach has been used, although by recent standards this might be considered as over sharpening].

(d) Subtraction of the Origin Peak.

The Patterson function

$$P(uvw) = (1/V^2) \sum_{-\infty}^{+\infty}\sum\sum |F(hkl)|^2 \cos 2\pi (hu/a + kv/b + \ell w/c) \quad \ldots.(1)$$

All atoms are at zero distance from themselves and as $\cos 0^\circ = 1$ this gives rise to a high peak at the origin, along with overall diffraction effects which may prevent the resolution of important peaks. The origin peak must therefore be subtracted from equation (1) to give the Patterson function without the origin peak

$$(1/V^2) \sum_{-\infty}^{+\infty}\sum\sum \left\{ |F(hkl)|^2 - \sum_{j=1}^{N} f_j^2 \right\} \cos 2\pi(hu/a + kv/b + lw/c)$$

In a two dimensional Patterson function peaks caused by adjacent atoms may not be distinguishable from the origin peak; subtraction of the origin peak may not however produce a previously unrecognisable peak and the correction applied to a two dimensional function for its own sake has relatively little value. It is assumed that

$$\sum_{j=1}^{N} f_j^2 = |F|^2 \quad ^{72}$$

and the Patterson function at the origin

$$(1/V^2) \sum_{-\infty}^{+\infty}\sum\sum \left\{ |F(hkl)|^2 - |F|^2 \right\} = 0$$

When "sharpening" the Patterson peaks it is however worthwhile to cancel simultaneously any peak which may occur at the origin and a general improvement of resolution may be expected.

(e) The Harker Section.

Harker[73] has suggested a very useful simplification of the Patterson method by which one can carry out a two dimensional summation using all of the three dimensional data. The method makes use of certain symmetry relationships: if, for example, there is a two-fold

rotation axis //b the effect of the symmetry operation on any atom is to produce another atom with the same y co-ordinate so that the function P(uvw) has a peak due to the interatomic distance between these two atoms in the plane v = 0. All the necessary information may then be obtained from evaluation of the Patterson function in this plane. This treatment can be applied to two dimensional data and although the method naturally becomes less powerful its advantage is its speed and the ready availability of the two dimensional data.

(f) Heavy Atom Method.

Very often the interpretation of a Patterson diagram is a matter of some difficulty and this applies particularly to a two dimensional projection where confusion arises because of the overlapping of vector peaks. The presence of a heavy atom can be a considerable help in the interpretation of such maps and indeed for many purposes it is desirable to introduce one.

The atomic number of the heavy atom should be great enough to surmount the large number of possible peaks due to lighter atoms: then the important peaks are these due to vectors joining the heavy atoms to each other and to the lighter atoms and these should stand out. If, happily, the heavy atom is situated at a centre of symmetry, or even an apparent one, then one can obtain the positions of the lighter atoms relative to the heavy atom at the origin and so get a direct picture of the structure. If the diffracting power of the heavy atom at a symmetry centre is greater than that of all the other atoms combined, its contribution to the structure factors will be greater than that of the lighter atoms and this will be positive; a direct Fourier synthesis can then be carried out. This was the case with platinum phthalocyanine[74] where the platinum was completely phase determining; this is probably the classical example.

In less favourable cases, when the heavy atom is situated at a general position and does not dominate the contributions of the lighter atoms, it may still be possible to pick out the vectors between the heavy

atoms. Binnie and Robertson successfully solved the structure of hexamethylene diamine dihydrobromide[75] by Patterson methods: the unit cell of this compound contains four molecules; there are eight bromine atoms in all so that there should be a total of fifty-six interbromine vectors, eight of these are due to distances between atoms reflected across the centre of symmetry, the remaining forty-eight fall into two sets of twenty-four; these are superimposed because of interatomic distances which are of equal length and parallel to each other. Binnie and Robertson were able to observe all these peaks on their vector map and moreover could assign co-ordinates to the bromine atoms by selecting eight special vectors arising from symmetrically related atoms after the method described by Harker[73]. It was then possible to proceed with the solution of the structure by the usual Fourier methods, using at first only the co-ordinates of the bromine atoms.

The Heavy Atom Method has its own disadvantages however and the principal atom may have such a concentration of scattering matter that it is not possible to determine the co-ordinates of the lighter atoms with any accuracy. This problem arose with the last structure when it was found that the peaks due to the lighter atoms were distorted and poorly resolved owing to diffraction effects from the bromine atoms. The greater absorption coefficients of heavier compounds make the estimation of intensities more difficult so that the benefits derived in the initial stages tend to be outweigh ed by subsequent disadvantages. For a large organic molecule it is not necessary that the atomic number of the heavy atom should be greater than the sum of that of the lighter atoms: the contribution to the measured intensity depends on the square of the scattering factor andif the square of the atomic number of the heavy atom is equal to the sum of the squares of the atomic numbers of the lighter atoms about three-quarters of the signs are likely to be correct. The scattering curvesof lighter atoms decrease more rapidly at larger angles than do the heavy atom scattering curves so that the scattering power of the heavy atom is effectively two or three times greater than it appears: moreover for a larger molecule the lighter atom

contributions have a fair chance of calcelling out. This means unfortunately that trouble may arise because of premature termination of series and it is necessary to obtain a reliable estimate of far out reflections to make full use of the method.

(g) The Isomorphous Replacement Method.

This method is very useful when there is a replaceable metal atom which has not sufficient electron scattering power for the Patterson method to be successful: an isomorphous compound may then be prepared using a heavier metal atom which can be located in the unit cell. The method depends on a difference effect between the two metal atom contributions to determine the phase relationships. For any particular zone of X-ray reflections given by each compound the positions of the reflections will be approximately the same and the only significant differences, i.e. in the intensities, will be due to the different scattering power of the two metal atoms: if both sets of intensities are put on to an absolute scale the contribution of the light atoms to the structure factors is constant, the difference in scattering power of the two heavy atoms is known so that signs can theoretically be determined.

The method has the advantage that the final structure can be worked out for the compound having the lighter atom, the absorption difficulties are minimised and a better estimation of atomic co-ordinates may be obtained.

Cork[76] successfully used this method in the study of the alums but its main application to organic structures was made by Professor Robertson in the study of the phthalocyanines.[77,78] In this case nickel phthalocyanine is isomorphous with the parent compound; the positions of the Ni atoms could be determined from symmetry considerations so that the heavy atom contribution to the structure factors in nickel phthalocyanine could be calculated. By comparison of their structure factors with the corresponding structure factors for phthalocyanine the phases were readily determined and the structures calculated. Speakman has used this method most successfully in the study of rubidium,

potassium and ammonium acid salts of some monobasic acids[2,3,5]. The method was exploited to the full in the study of the acid salicylates of ammonium, potassium and rubidium[5]. The rubidium atom was located by Patterson methods so that the position of the potassium atom could be assmed and the expected absolute difference in pairs of structure factors calculated. As it was expected from previous experience that the average structure factor for the rubidium salt would be about 1.8 times that for the potassium salt, it was possible to put both sets of structure factors on an approximately absolute scale, to extend the treatment to the ammonium salt and therefore work out the structure of the most favourable compound.

(h) The Correctness of the Structure

Some assessment of the correctness of a structure is given by the agreement index $$R = \frac{\Sigma \left| |F|_{obs} - |F|_{calc} \right|}{\Sigma |F|_{obs}}$$

where F_{obs} and F_{calc} are observed and calculated structure factors respectively. F_{obs} and F_{calc} may be extended to include the unobserved terms. The value of R should diminish as the structure improves but this index is only of relative value in comparing different sets of calculated structure factors with the observed and has no absolute significance.

PRELIMINARY DATA.

Owing to the complexity of crystal structure analysis it is often worthwhile, where possible, to make preliminary measurements on related compounds and to examine the data in the light of the information required and with relation to any of the techniques which might be applied to those data to facilitate the structure analysis.

In the present case the object of the study was to determine the presence or absence of intra-molecular hydrogen bonding in the γ-resorcylate anion: this information can be obtained either from the free acid or its salts. A structure analysis of the acid might have yielded hydrogen atom positions and wouldhave permitted a comparison with salicylic acid. Unfortunately the anhydrous acid was found to be very unstable and preliminary data were collected for the hydrated acid and for the metal salts.

The similar axial lengths of the crystal of the acid hydrate indicated comparative difficulty in solution of the structure and in no one zone couldit be hoped to get complete resolution of the atoms.

The metal salts offered a more attractive prospect. Rubidium and potassium isomorphs could be prepared, each with one short axis and this suggested good resolution in one zone and the possibility of solution by the Isomorphous Replacement Method.

Accordingly the crystal structure analysis has been carried out on potassium 2:6-dihydroxy benzoate. The preparations of the acids and thevarious salts are given in the appendix.

2:6-DIHYDROXY BENZOIC ACID

1. Introduction

No detailed study of 2:6-dihydroxy benzoic acid $C_7H_6O_4$, either chemical or structural, has as yet been carried out and there is little mention of it in the literature. It was first mentioned in 1880 by Senhofer and Brunner[79] who were studying direct methods for the introduction of the carboxyl group into phenols. They found that in the preparation of "α resodi-carboxylic acid" $C_8H_6O_6$, 2:4-dihydroxy benzoic acid was formed along with a small quantity of yet another dihydroxy acid. This last acid was found to be fairly soluble in hot water, more so than in cold water and gave a purple colouration with a weak solution of ferric chloride and an intense blue colouration with a strong solution. They found that the acid reduced Fehling's solution at the boiling point but had no effect on ammoniacal silver solution. Senhofer and Brunner point out that only three dihydroxy benzoic acids are possible, the 3:5-dihydroxy benzoic acid, the 2:4 acid and a 2:6 or γ-resorcylic acid. Having established that the new acid isolated was neither of the first two quoted they assumed by a process of elimination that it must be the 2:6 acid. The physical and chemical properties quoted agree with those now cited for γ-resorcylic acid and Senhofer and Brunner's assumption would appear to be correct.

It seems almost a foregone conclusion that dichelation will be found in the acid as all evidence pertaining to both the acid and related compounds favours such a state, and also that the acid will exist as a dimer. 1:8-dihydroxy anthraquinone, in which one oxygen atom as in salicylic acid forms two hydrogen bonds, and 2:2-dihydroxy benzophenone have been shown to be dichelated[6] and it is very likely that γ-resorcylic acid should also be dichelated. Di-orthosubstituted benzoic acids (involving electronegative substituents) have been shown to be still stronger acids than their mono-orthosubstitued analogues and a study of them has been made by Lloyd and Sudborough[80]. Ongley[23] has examined the solubility of 2:6-dihydroxy benzoic acid and compared it with that of o- m-, and p-hydroxy benzoic acids and 2:4, 2:5 and 3:4 dihydroxy benzoic

acids. His results show that if a dihydroxy acid has one chelated and one free hydroxyl group the solubility follows the pattern of the m- and p- rather than the o- mono-acid. The solubility of the 2:6-dihydroxy acid resembles those of the ortho- rather than the meta- and para and it may be said that the solubility evidence too supports the theory that the acid is dichelated. Baker[81] has quoted the dissociation constant of 2:6-dihydroxy benzoic acid, $K = 5 \times 10^{-2}$ and has suggested that the increased strength going from salicylic to γ-resorcylic acid might be due to a double chelated effect involving both equivalent hydroxyl groups.

2. Crystal Data.

2:6-Dihydroxy benzoic acid monohydrate $C_7H_6O_4.H_2O$; molecular weight 172.07; m.pt., varies according to method of crystallisation and rate of heating, 150-170°C; crystals used for X-ray work had a m.pt. 161°C; orthorhombic; $a = 6.77 (\pm .03)$, $b = 9.67 (\pm .04)$, $c = 11.92 (\pm .02)$ Å; volume of unit cell 780.4 Å^3; density, calculated, 1.46, found 1.48; four molecules per unit cell; total number of electrons per unit cell $F(000) = 320$; absorption coefficient for X-rays ($\lambda = 1.54$ Å), $\mu = 10.79$ cm.$^{-1}$.

Absent spectra: 0kl when k + l is odd, hk0 when h is odd, h00 when h is odd, 0k0 when k is odd, 00l when l is odd. Space group is C_{20}^9 $Pna2_1$, or D_{2h}^{16} Pnma; molecular symmetry nil. (see later)

3. Experimental.

a) Crystallisation.

The crude substance was crystallised from a water/methanol mixture, care being taken that the temperature did not go above 75°C, lest the acid decomposed to the quinone. In other solvents (e.g. water, alcohol), the crystals readily changed through pink to purple and became almost black. In methanol the crystals remained colourless over a considerable period. The solutions containing the acid were filtered warm and allowed to crystallise slowly by placing an evaporating basin of solution in a basin of water at the same temperature.

The crystallisations from water gave fairly thin long plates, those from methanol/water 1:1 gave plates rather thicker and those from ethanol/water 1:1 gave plates thicker still, but showing marked clumping.

The crystal used was a uniform rectangle of dimensions .2 x .2 x .6 mm. This was cut to give fairly uniform cross sections perpendicular to the three axes.

The cross sections were:

1) (0kl) zone .20 x .20 mm.
2) (h0l) zone .25 x .20 mm.
3) (hk0) zone .25 x .20 mm.

b) Determination of Crystal Data

Copper K α radiation, $\lambda = 1.54$ Å was used in all measurements. Rotation, oscillation and zero and first layer line moving film photographs were used, these last to determine the space group.

c) Measurement of Density and Number of Molecules in Unit Cell.

The density, d, was found by flotation of small crystals in a mixture of chlorobenzene and carbon tetrachloride. The value obtained was 1.48. The number of molecules (n) per unit cell was calculated using the formula $n = \frac{Vd}{M}$ where V is the volume of the unit cell in c.cs., M is the molecular weight of the compound. This expression requires to be divided by 1.66×10^{-24}, the weight in gms. of an atom of atomic weight 1.000. n was found to be 4. The calculated value of the density using $n = 4$ is found to be 1.46, which is in good agreement with the observed value of 1.48.

4. Discussion

As in most orthorhombic systems there is a choice of space groups, one centred and one non-centred.

The centred space group, Pnma has eight equivalent positions in the unit cell

$x,y,z;\ \ ^1/_2 + x, ^1/_2 - y, ^1/_2 - z;\ \ \bar{x}, ^1/_2 + y, \bar{z};\ \ ^1/_2 - x, \bar{y}, ^1/_2 + z;$

$\bar{x},\bar{y},\bar{z};\ \ ^1/_2 - x, ^1/_2 + y, ^1/_2 + z;\ \ x, ^1/_2 - y, z;\ \ ^1/_2 + x, y, ^1/_2 - z$

and four special positions

$x, ^1/_4, z;\ \bar{x}, ^3/_4, \bar{z};\ ^1/_2 - x, \ ^3/_4, \ ^1/_2 + z;\ \ ^1/_2 + x, \ ^1/_4, \ ^1/_2 - z$

Now density determinations have indicated that there are only four molecules in the unit cell. To fit in with the space group Pnma, either the molecule must possess a centre of symmetry, which it obviously does not, or the four molecules must occupy special positions on the mirror plane. If this is the case and the molecule is lying parallel to the b axis, the OkO spots will have greater amplitudes than the other axial spots and the intensities will fall off as the ξ value increases. Moreover, the intensities of the reflections in the hOl zone will be relatively greater than in the other two zones.

This does not appear to be the case, and the crystal is probably non-centred.

Apart from space group considerations, the similar axial lengths of the crystal indicate comparative difficulty in solution of the structure as in no one zone could it be hoped to get complete resolution of atoms, but instead overlapping effects. The original plan, to compare the anhydrous acid with salicylic acid, had to be abandoned owing to instability of the anhydrous acid, and at this stage it was decided to investigate the structure of the anion, where the presence of a heavy cation might facilitate the solution of the structure.

POTASSIUM 2:6-DIHYDROXY BENZOATE

1. Crystal Data

Potassium 2:6-dihydroxy benzoate $KC_7H_5O_4$; molecular weight, M, 192.2; m.pt. dec. above 226°C; monoclinic prismatic;

Axial lengths

$a = 3.94 \pm .02$ Å

$b = 15.10 \pm .01$ Å

$c = 13.37 \pm .02$ Å $\quad \beta = 99° 11' \pm 30'$

Volume of unit cell = 785.12 Å^3; d, calculated = 1.63, d, measured by flotation = 1.66.

Four molecules of $KC_7H_5O_4$ per unit cell;

Total number of electrons per unit cell, F(000) = 392

Absorption coefficient for X-rays ($\lambda = 1.54$ Å) $\mu = 57.75$ cm.$^{-1}$

Absent spectra:- (h0l) when h + l odd, (0k0) when k odd, (00l) when l odd.

Space group, $P2_1/n$. Molecular symmetry, nil.

2. Experimental

a) Determination of Crystal Data

Copper Kα radiation, $\lambda = 1.542$ Å, was employed, the Kβ radiation being eliminated by means of a nickel filter. Rotation, oscillation, and zero and first layer-line moving film photographs were taken about each of the unit cell axes. Series of equatorial layer-line moving film photographs were taken about the three axes and a series of first layer - line moving film photographs was taken about the a axis. The axial lengths were measured from the rotation photographs. The oscillation and moving film photogrphas indicated that the crystal was monoclinic. Systematic absences were noted from the moving film photographs.

(b) Measurement of Density and Number of Molecules in the Unit Cell.

The density, d, was found by flotation of small crystals in a mixture of carbon tetrachloride and bromoform, and the value obtained was 1.66. The number of molecules (n) per unit cell was calculated using the formula, $n = \frac{Vd}{M}$, where V is the volume of the unit cell in c.cs., and M is the molecular weight of the compound. This expression is divided by 1.66×10^{-24}, the weight in grams of an atom of atomic weight 1.000. n was found to be 4 to the nearest whole number. The calculated value of the density, using n = 4, is found to be 1.63, which agrees with the observed value 1.66.

(c) Measurement of the Intensities of the X-ray reflections.

The moving film photographs were employed to record the (0kl), (h0l) and (hk0) reflections which were used in the structure determination. The intensities were estimated visually on a relative scale by the multiple film technique[82]. The intensities were corrected for Lorentz and polarisation factors, and the resulting structure amplitudes, $|F_{obs}|$, scaled by comparison with the calculated values are given in Table VI. In Table 1 are shown the number of intensities observed in each zone at the commencement of the investigation, the range of intensities observed and the cross sections of the crystals used.

Table I.

Zone of Reflections	Reflections Observed	Reflections possible for CuK_α	Range of Intensities	Cross Sections of Crystals used
0kl	118	263	2700/1	.20 x .24 mm.
h0l	55	70	1800/1	.36 x .45 mm.
hk0	56	80	2600/1	.36 x .42 mm.

An additional 61 reflections were later recorded in the 0kl zone making a total of 179 reflections observed and the range of intensities observed became 3500/1.

(d) Patterson and Fourier Analyses.

The first Patterson projection on the Okl zone (fig. I) was computed at 450 points on the asymmetric unit. The b axis was divided into 60 parts and the c axis into 30 parts so that the intervals of division were .252 and .440 Å respectively. The second Patterson projection on the Okl zone, (fig. II), was computed at 900 points on the asymmetric unit. In this case both the b and c axes were divided into 60 parts, so that the intervals of division were .252 and .220 Å respectively. The summations were carried out using Beevers-Lipson 6° [83] strips. The positions of the contour lines were obtained by graphical interpolation of the summation totals, by making sections of the rows and columns.

The first two Fourier syntheses were computed on the harmonic balance designed by Vand[84]. Using this method no graphical interpolation was necessary. For the Fourier syntheses on the hkO and hOl reflections, the electron density was computed at 450 points, the a axis being divided into 30 parts and the b and c axes divided into 60 parts so that the intervals of division were .131, .252 and .220 Å respectively. For the Okl zone the electron density was calculated at 900 points and in this case both axes were divided into 60 parts. Most of the Fourier summations were carried out using the 3° Beevers-Lipson strips.[85] The last electron density projection on the(100)plane was calculated using the digital computer designed by Professor Robertson[86]: minor modifications were made in the method so that terms of index greater than 15 could be included.

In the Vth and VIth electron density projections the atomic centres were calculated by a least squares method described by Dr. J.D. Dunitz[87] and attributed by him to Dr. V. Schomaker. Generally, the atomic centres were estimated visually.

3. Analysis of the Structure.

Owing to the shortness of the a axis it was assumed that the plane of the benzene ring would be almost perpendicular to it and that good resolution would be obtained by projection down that axis.

A survey was made of the intensities of the Okl reflections according to the Wilson method[88] for detecting a centre of symmetry and ratios; $|F|^2 / |F^2|$ were derived for ranges of $\sin\theta$. The average of these ratios was .60 and a centre of symmetry was assumed.

The presence of a heavy atom suggested solution of the structure by Patterson methods. For the space group $P2_1/n$ there are four equivalent positions in the unit cell,

x,y,z; -x,-y,-z; ½ + x, ½ - y, ½ + z; ½ - x, ½+ y, ½ - z

and, as there are four stoichiometric molecules in the unit cell, one molecule forms the asymmetric unit and the potassium ions must occupy general positions. This is not the most favourable case but it was hoped that the Patterson method would serve to determine the potassium positions. There are 48 atoms in the unit cell, discounting hydrogen atoms, so that there are (48 x 47) interatomic vectors. Only twelve of these are due to the potassium ions however.

A Patterson projection was evaluated on the Okl data. The resulting map is shown in Fig. 1. This synthesis was not helpful. As can be seen, several high peaks appear on the diagram but it was not possible to decide to which pair of atoms each peak referred. It seemed likely from the map that some of the smaller peaks due to the lighter atoms were overlapping and creating false maxima and that the potassium was not heavy enough to surmount these spurious effects. Another feature of this map was a large peak at the origin.

A 'sharpened' Patterson synthesis was now evaluated and, as previously described, at the same time an attempt was made to eliminate the peak at the origin and the accompanying diffraction effects.

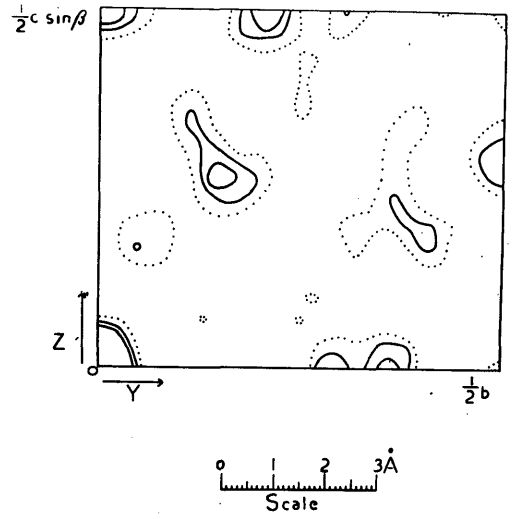


Fig. I.

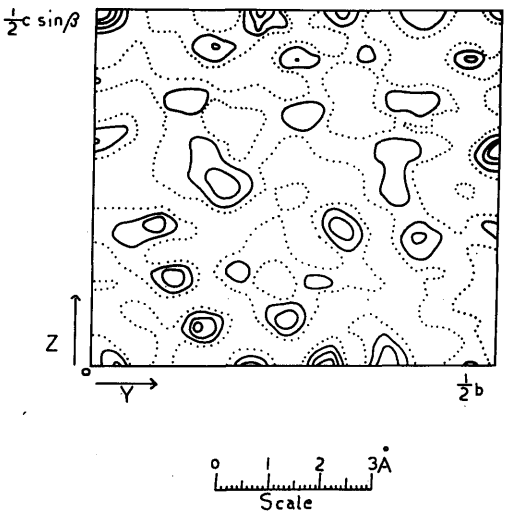


Fig. II.

Fig. I. Patterson projection on (100) plane of potassium 2:6-dihydroxy benzoate.

Contour-line scale arbitrary.

Fig. II. "Sharpened" Patterson projection on (100) plane of potassium 2:6-dihydroxy benzoate.

Contour-line scale arbitrary.

Instead of F^2 the coefficients in this synthesis were $(S^2 - \bar{S}^2)$ where $S^2 \sim F^2/\hat{f}^2$ and $\hat{f}$ is a unitary scattering factor derived from empirical scattering curves. $\bar{S}^2 = \Sigma S^2/n$ where n is the number of terms within a limiting circle defined by the minimum radius from the origin which would include all observed terms and includes terms for which $F^2 = 0$. The scattering curves used at this stage were those employed by Dr. Speakman in the solution of the structure of potassium hydrogen bisphenyl acetate[2] and derived from the James and Brindley data[89] (see Appendix II, table VIII).

The results of this synthesis are shown in fig.II. The map shows a marked improvement on the previous one but still no full interpretation could be given to all the peaks. It now seemed that the potassium ions could not produce a vector peak large enough to dominate the peaks due to the lighter atoms and it was decided to try the isomorphous replacement of potassium by rubidium in the hope that this might give more definite results.

The isomorphous rubidium salt was prepared with some difficulty (see Appendix) and relative intensities of the reflections in the Okl zone were measured. In order to apply the isomorphous replacement method it was necessary that the observed intensities for both salts should be on an approximately absolute scale so that comparisons could be made. This was done according to the method described by Wilson.[72]

Using the absolute structure factors for the OkO and OOl planes, two "difference" Pattersons were carried out. For corresponding planes the structure factor for the potassium salt was subtracted from that for the rubidium salt; the contribution of the lighter atoms thereby cancels out and only the difference in contribution due to the heavy atoms remains i.e. rubidium - potassium.

Neither of the one dimensional projections could be interpreted. In such a projection all of the peaks which would appear in a two dimensional projection are projected on to the lines $y = o$ and $z = o$ and in unfavourable cases such as this may overlap and fail to give resolution.

What did prove fruitful was a two dimensional line synthesis carried out on the rubidium salt according to Patterson-Harker methods.

For the space group $P2_1/n$ there is a screw axis //b and glide planes at ¼b and ¾b.

The equivalent points for the 0kl projection are

$$y,z;\quad -y,-z;\quad \tfrac{1}{2}-y,\ \tfrac{1}{2}+z,\ \text{and}\ \tfrac{1}{2}+y,\ \tfrac{1}{2}-z$$

and these give rise to twelve potassium vectors as follows and as shown in fig III

$$2y,-2z;\quad -2y,-2z;\quad 2y,2z;\quad -2y,2z;\quad -\tfrac{1}{2},-\tfrac{1}{2}\ -2z;$$

$$\tfrac{1}{2},\tfrac{1}{2}-2z;\quad -\tfrac{1}{2}+2y,-\tfrac{1}{2};\quad \tfrac{1}{2}+2y,\tfrac{1}{2};\quad \tfrac{1}{2}-2y,\tfrac{1}{2};\quad -\tfrac{1}{2}-2y,-\tfrac{1}{2};$$

$$\tfrac{1}{2},\tfrac{1}{2}+2z;\quad -\tfrac{1}{2}.\ -\tfrac{1}{2}+2z.$$

Of these there are eight special vectors giving rise to four special positions

$$\tfrac{1}{2}-2y,\tfrac{1}{2};\quad \tfrac{1}{2},\tfrac{1}{2}+2z;\quad \tfrac{1}{2},\tfrac{1}{2}-2z;\quad \tfrac{1}{2}+2y,\tfrac{1}{2}.$$

Therefore, to obtain all the information, the two dimensional summation need only be done along the lines ½b and ½c.

From the projections shown in fig IV the co-ordinates of the rubidium ion were established as given below

$$y \text{ peak at } \frac{12.6}{60} \quad \therefore \quad y = \frac{17.4}{2 \times 60} \qquad (\tfrac{1}{2}-2y,\ \tfrac{1}{2})$$

$$= .145$$

$$z \text{ peak at } \frac{16.8}{60} \quad \therefore \quad z = \frac{16.8 - 30}{2 \times 60} \qquad (\tfrac{1}{2},\ \tfrac{1}{2}-2z)$$

$$= .890$$

The positions could now be confirmed from the peaks on the sharpened Patterson synthesis (fig II) and on the original Patterson Synthesis (fig I). Now, using only the co-ordinates for the rubidium and potassium ions respectively, structure factors were calculated for both salts according to the equation

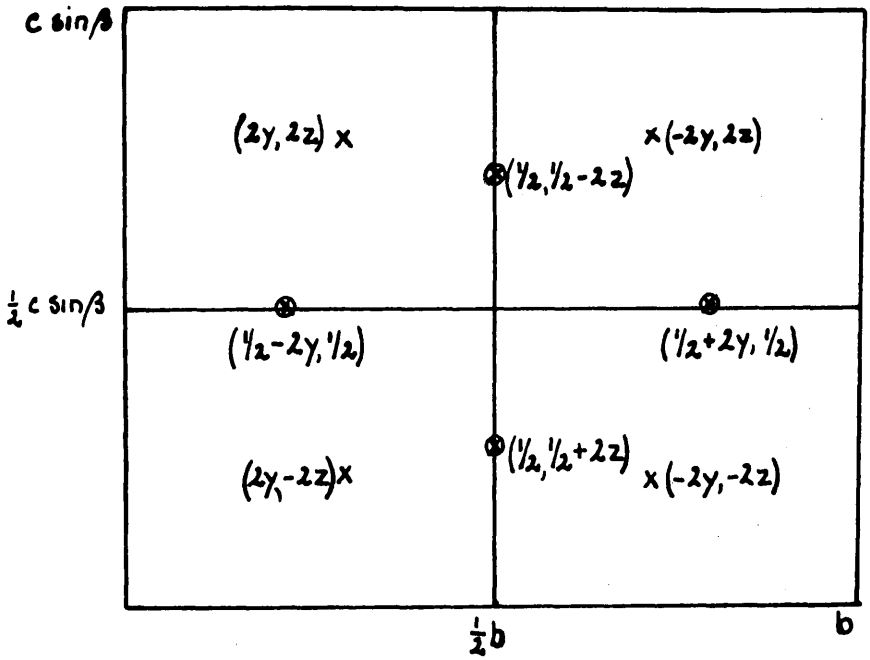


Fig.III. Theoretical distribution of vector peaks on Patterson projection on (100) plane for the space group $P2_1/n$.

x = single peak

⊗ = double peak

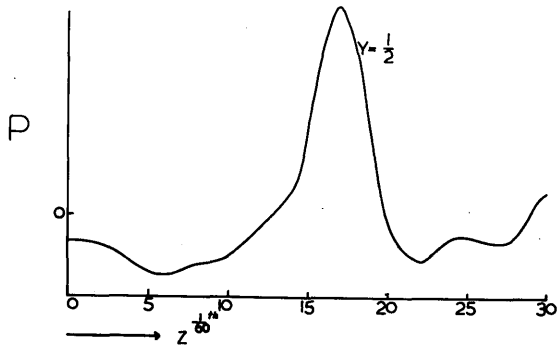


Fig. IVa

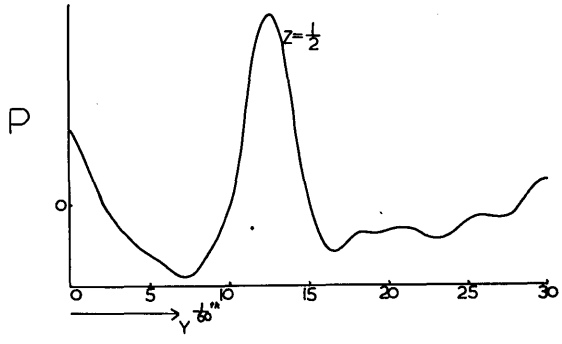


Fig. IVb

Figs.IVa and b. Two dimensional Patterson line syntheses on Rubidium 2:6-dihydroxy benzoate.

$F = 2[\cos 2\pi(ky + lz) + \cos 2\pi(ky - lz)$ when $k + l$ is even

and $F = 2[\cos 2\pi(ky + lz) - \cos 2\pi(ky - lz)$ when $k + l$ is odd

The scattering curve for rubidium was derived from the potassium scattering curve by applying the ratio fRb/fK, calculated from the Hartree scattering curves[89] at .1 intervals of $\sin\theta/\lambda$ (Appendix 2, Table VII, line 2).

The various stages in the refinement can now be followed from Table II, page 60. This table lists the Fourier syntheses evaluated on the Okl data, the number of terms included in each synthesis, those included with incorrect signs (derived from comparison with the final structure factors) and finally, the figures of merit derived when structure factors had been calculated after each successive Fourier synthesis.

By comparison of the observed and calculated structure factors for both salts it was possible to attribute signs to 50 observed structure factors for the potassium salt. These were used as coefficients in a Fourier synthesis evaluated using Vand's electron density balance.[84] This balance was a prototype but it was thought that this method would serve very well for a preliminary Fourier synthesis and would indicate whether or not the isomorphous replacement method had been successful. The first synthesis could not be interpreted but in a second synthesis nine more terms were included and it is now interesting to note, on comparison with the final structure factors that all 59 signs were correct. The results of the synthesis are shown in fig. Va.

This map was difficult to interpret and the structure of the molecule was not easily reconciled with its contours. The environment of the potassium proved at once a problem and a guide, as it had not been expected to find the potassium ion associated with the four oxygen atoms of the molecule. The oxygens of the carboxyl group O_1 and O_2 were eventually fixed by a process of elimination from consideration of the maximum $O_1 - O_2$ projected bond length likely to be present in projection down a 3.94 Å axis. After several trials based on the K, O_1 and O_2 positions co-ordinates were tentatively assigned to all the other atoms

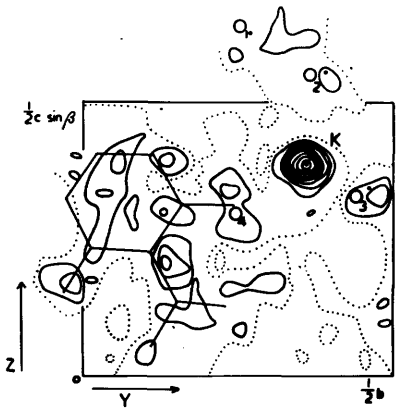


Fig. Va

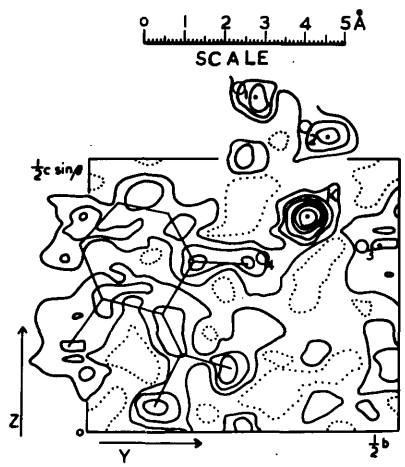


Fig. Vb

Fig. Va: Second electron-density projection on (100) plane of potassium salt evaluated using Vand's electron density balance and including 59 terms.

Contour-line scale: 2 electrons per sq. Å

Line of unit electron density broken.

Fig. Vb: Third electron-density projection on (100) plane of potassium salt including 96 terms.

Contour-line scale: 2 electrons per sq. Å

Line of zero electron density broken.

of the molecule. Structure factors calculated using these co-ordinates gave a figure of merit 57%. It was then possible to attribute signs to another 37 planes making a total of 96 planes which were included in the next Fourier synthesis. This synthesis was evaluated using Beevers-Lipson strips and the electron density projection is shown in fig. Vb. The agreement index fell to 46% and this lowering of the discrepancy suggested the possibility of further refinement by Fourier methods.

Refinement was continued until a discrepancy of 39.1% was reached. At this stage the potassium scattering curve was modified (Appendix 2, Table VII, line 5) and the discrepancy fell to 37.6% before the next Fourier synthesis, which reduced it to 26.5%. Yet another Fourier synthesis only brought the R value down to 24% and it was decided to do a "difference" or $(F_{obs} - F_{calc})$ synthesis according to the method of Cochran.[90]

All the atomic co-ordinates were shifted, except those of the potassium ion, which lay practically on a zero position. The agreement index fell to 19.8%. This synthesis indicated some discrepancy in the oxygen and carbon atom scattering curves and these were accordingly altered.

In the first instance a composite carbon oxygen scattering curve was derived from the McWeeny[91] data and the appropriate temperature factor was applied; (Appendix 2, method 1). The potassium curve was rescaled and modified slightly.

Meanwhile, Speakman had developed a least squares method for varying several scattering curves independently in order to get the best agreement between observed and calculated structure factors and this method was applied to structure factors grouped into small ranges of $\sin^2\theta$. This technique was designed for use in the study of acid salts where there is an ionisable heavy atom along with carbon and oxygen atoms and where the use of a composite scattering curve might seem unwise. The method was used successfully in the solution of the structure of Linstead compound B[92] and is similar to that described by Luzzatti[93]. The three scattering factors were accordingly modified as described in Appendix 2, method 2. This second method produced a lower discrepancy and the scattering curves thus derived were retained.

Despite the lowering of the agreement index to 17.2% comparatively few signs had altered since the evaluation of the difference synthesis and the benzene ring remained most irregular. As the regular dimensions of the benzene ring have been established since the accurate quantitative analysis of naphthalene and anthracene by J.M. Robertson[67,68] these dimensions were now used and the best fit over the existing ring taken This involved alteration of the y and z co-ordinates of C_2, C_6 and C_4 It was thought that, should the structure be false, this treatment would probably raise the value of R.

The R value fell to 16.8% and attention was meanwhile turned to the other two zones.

Owing to the shortness of the a axis and the good resolution obtained on the (100) projection it seemed that little information would be gained from electron-density projections down either the b or the c axes and that the solution of the structure would require to proceed by other methods.

From the Okl projection it was clear that the structure depended on the packing of the oxygen atoms round the potassium ion so that the first object was to ascertain its x co-ordinate.

The possibility of refinement using the 1Kl data as described by Cochran[94] and carried out by Speakman for Linstead compound B[92] was considered and rejected, as the potassium does not lie at a centre of symmetry and its position would in any case require to be found by trial methods.

Determination of the third potassium co-ordinate by Patterson methods using the hOl and hkO data, was also contemplated but it was thought that potassium oxygen vectors would confuse the issue. It is interesting now to consult figs. VI and VII and realise that such an approach would have been unsuccessful; in fact the contribution of the potassium ion had to be removed from the (010) electron-density projection before the oxygen maxima could be located.

From consideration of the far out hOl and hkO spectra to which it may be assumed that the heavy ion makes a maximum contribution it was

possible to assign an approximate position to the heavy ion. It was now possible to calculate approximate positions for the surrounding oxygen atoms.

From the potassium-oxygen distances in the Okl projection, (for numbering see fig. IX), it appeared that the cation K''' was bonded to two hydroxyl oxygens, O_4''' and O_3'' and to one of the oxygen atoms of the carboxyl group O_2' but had little or no attraction for the other, O_1' : this last deduction was made from the apparently short bond length between K''' and O_2' and the short projected $O_1' - O_2'$ distance, suggesting a considerable tilt of the carboxyl group, about 32°. From the sum of the ionic radii quoted by Pauling[6] for potassium and oxygen and the values for bonded potassium and oxygen quoted by Skinner and Speakman[3] a reasonable K-O bond length was assumed to be about 2.8 Å. Thus, from the y and z co-ordinates two approximate x co-ordinates could be assigned to each of the oxygen atoms O_2', O_4''' and O_3''. Various possibilities were reduced by relating these oxygen atoms to others in the unit cell by symmetry operations and by consideration of the difference in height between the oxygen atoms within one molecule.

Carbon and oxygen bond lengths were assumed in the first instance from Cochran's data on salicylic acid[22] and, now that the y and z co-ordinates were available, it was possible to calculate that the benzene ring must be tilted along the line of the hydroxyl groups, with little or no tilt perpendicular to this direction. The direction of tilt could not be calculated.

The oxygens bonded to K''' can all be related to oxygens of molecule 1. O_3'' is related to O_3' by a centre of symmetry and, because of the glide plane, the x co-ordinate of O_4' must differ by $1/2$ from that of O_4'''. x co-ordinates of O_1' follow from those of O_2' and for the four oxygens were considered which were consistent with the tilt of the molecule and the fact that O_2' and O_3' must be near the same level.

The carbon atoms were assumed to be planar with the hydroxyl oxygens and x co-ordinates were calculated for them.

It was not possible to determine the co-ordinates sufficiently accurately to get a reasonable discrepancy, as of course the potassium position was only very approximate. Accordingly a ghost h0l projection was drawn up and the heavier atoms of all the molecules were moved, keeping their z co-ordinates constant, until a reasonable fit was obtained with regard to bond lengths, Van der Waals distances etc.. There are three strong reflections in this zone $\bar{1}01$, 101 $\bar{1}05$ and the molecules were placed so that these planes should have a high structure factor. The structure factors calculated gave a discrepancy of 61%. This was rather high but inspection of the discrepancies for individual planes suggested that the structure was probably correct. 39 of the observed 58 spectra were used as coefficients for a Fourier synthesis. In the resulting electron-density projection the benzene rings overlapped badly but the potassium ion and O_2 and O_4 atoms showed up quite clearly: O_1 was merged with the cation but even so it was possible to obtain better co-ordinates for K, O_2, O_4 and O_1. The projection was of little help in indicating the other atomic positions although the general position of the molecules could be found. After very many trials, from which it was deduced that the structure was probably planar, co-ordinates were obtained. Meanwhile the y and z co-ordinates of C_2 were altered so as to improve the alignment of C_1, C_2 and C_5. The new co-ordinates brought the discrepancy down to 39.6%.

This last projection suggested that some guide to the potassium position and the orientation of the rest of the molecule might be obtained from a projection on to the (001) plane. This proved to be so and from the co-ordinates thus derived a discrepancy of 31% was calculated for the hk0 zone. Now, considering both the (010) and (001) projections, refinement proceeded mainly by trial methods. The latest electron-density projection on the (001) plane is shown in fig. VI; 52 out of 56 possible terms were included. From this map, positions for the potassium ion were picked until the best agreement of calculated and observed structure factors in both zones were obtained. The potassium contribution was then subtracted from the structure factors for the h0l zone and a further Fourier synthesis evaluated. This method was quite successful

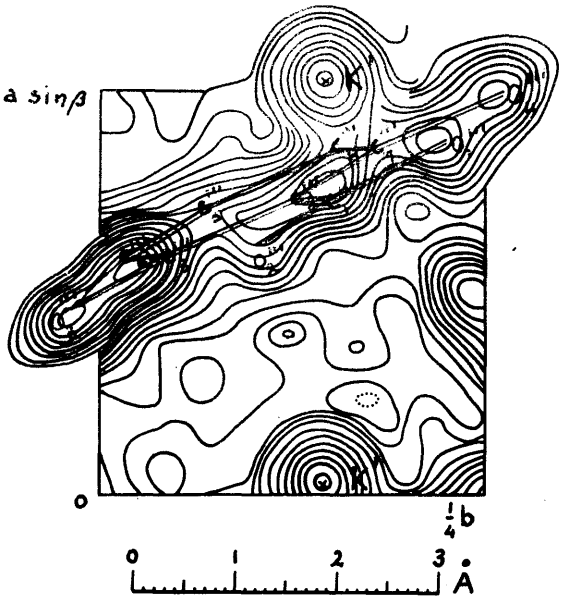


Fig. VI

Electron-density projection on (001) plane of potassium salt.

Contour-line scale: 8 electrons per sq. Å except at heavy atom where only every third contour is shown.

Line of unit electron density broken.

The positions of the potassium ions are indicated by crosses.

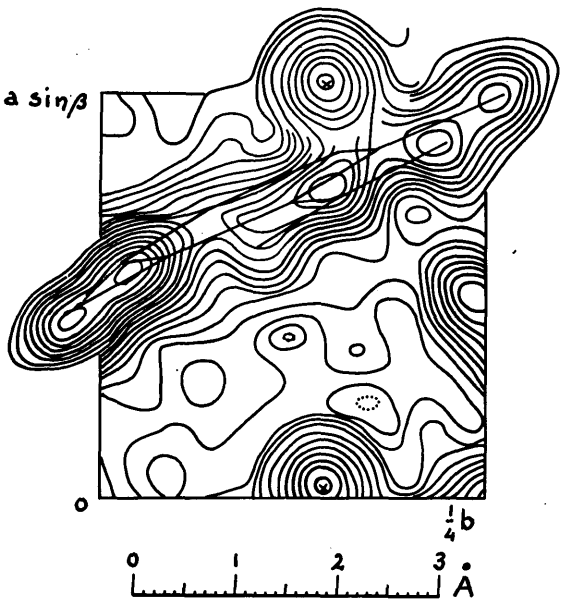


Fig. VI

Electron-density projection on (001) plane of potassium salt.

Contour-line scale: 8 electrons per sq. Å except at heavy atom where only every third contour is shown.

Line of unit electron density broken.

The positions of the potassium ions are indicated by crosses.

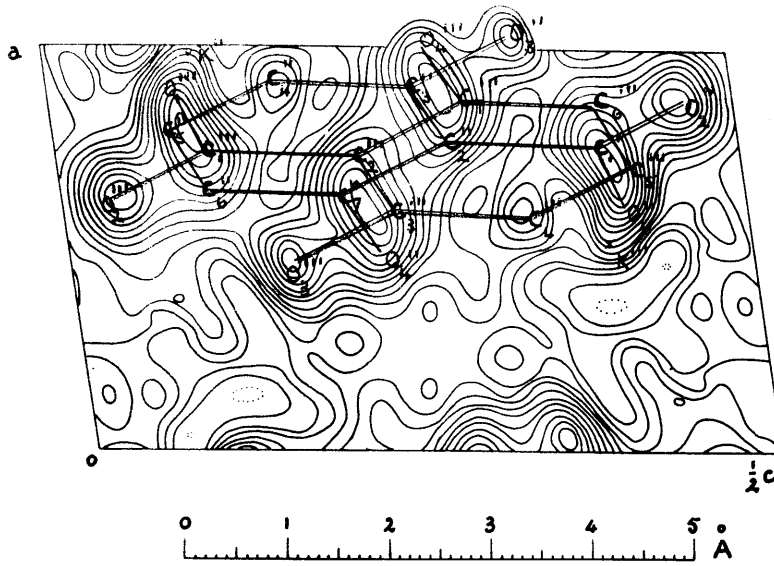


Fig. VII.

Electron-density projection on (010) plane of potassium salt with potassium contribution removed; (the potassium positions are indicated by crosses).

Contour-line scale: 8 electrons per sq. Å.

Line of unit electron density broken.

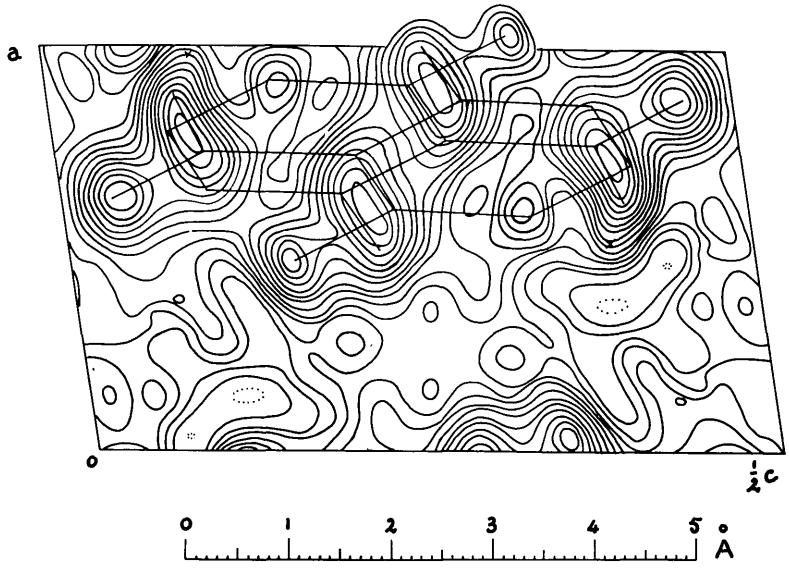


Fig. VII.

Electron-density projection on (010) plane of potassium salt with potassium contribution removed; (the potassium positions are indicated by crosses).

Contour-line scale: 8 electrons per sq. Å.

Line of unit electron density broken.

and gave better resolution of O_1. 49 of the 56 observed terms were included in the synthesis. The electron density map is shown in fig VII. Co-ordinates were assigned to all atoms and the discrepancies calculated were 23.4% for the h0l reflections and 22.1% for the hk0 reflections.

At this stage attention was turned again to the 0kl zone, for while the discrepancy was 17% the benzene ring was still badly distorted. Alteration of the C_2, C_6 and C_4 co-ordinates, so that the ring became more regular, had only reduced the discrepancy to 16.8%. Now it was feared that the experimental data might be in error so a longer series was taken and 61 more reflections were observed. Structure factors were again calculated and the discrepancy rose to 19.93%. After the evaluation of a Fourier synthesis which contained 57 more terms than the previous synthesis, this figure fell to 16.03%. After the IXth Fourier synthesis the discrepancy became 14.9% and as the synthesis included all but two of the structure factors it seemed that the limit of the Fourier method had been reached. Accordingly a Booth synthesis[95] was computed in order to correct for any errors which might have arisen due to premature termination of series. The co-ordinates thus found were used to correct those found from the IXth electron-density projection.

The resolution of the atoms was still disappointing and the refinement of the h0l and hk0 zones was very poor. In order to explore the possibilities of faulty scattering curves another difference synthesis was computed using 135 terms. This indeed indicated considerable discrepancy in the scattering factors and it was decided to employ the theoretical atom scattering curves of Berghuis et.al.[96] for K, C and O. Structure factors were calculated using these uncorrected scattering factors and the calculated and observed structure factors were each summed over small ranges of $\sin^2\theta$ to obtain the ratio

$$\frac{\sum F_{obs}}{\sum G f_B} = \exp - B (\sin\theta/\lambda)^2$$

(f_B is the theoretical scattering factor and B is the temperature factor).

This ratio was plotted against $\sin^2\theta/\lambda^2$ and from the graph a new scaling factor, C = .5, and temperature factor, B = 2.4 was calculated. The discrepancy fell to 11.5%. A further difference synthesis indicated a small modification of the temperature factors and a small shift in co-ordinates. The discrepancy in the 0kl zone now became 9.4%. Using these structure factors a final Fourier synthesis was computed. All of the observed reflections were included in the synthesis; there were two terms more than in Fourier IX and there were eight changes of sign. Most of these sign changes applied to fairly small structure factors, none greater than 11. The scaling factor has altered from .38 to .48. The electron-density map is shown in fig. VIII.

Now the new z co-ordinates were marked on the 010 electron density map but no significant change in the x co-ordinates is apparent. A planar structure was assumed and x co-ordinates for the carbon atoms were calculated as before from the plane equation

$Ax + By + Cz + D = o$ where x,y and z are fractional co-ordinates.

The values of B/A, C/A and D/A in best agreement with the x co-ordinates found for the oxygen atoms are 1.79082, -.391361 and -.62773.

Structure factors were calculated for the h0l reflections using the new co-ordinates and scattering factors and the figure of merit fell from R = 23.4% to 17.8%; omitting the $\bar{1}05$ and 101 reflections which are obviously weak, owing to secondary extinction, R = 14.2%. Only two small terms have changed sign since the last Fourier synthesis was computed.

The discrepancy calculated for the hk0 reflections is 20.2% and when the extinguished reflections 130 and 120 are omitted this becomes 20.03%. There are no sign changes since the last Fourier synthesis was computed but four more terms could now be included.

The scattering curves have changed appreciably from those previously used and it is quite obvious that the slow speed of refinement was due to faulty scattering curves which produced misleadingly good

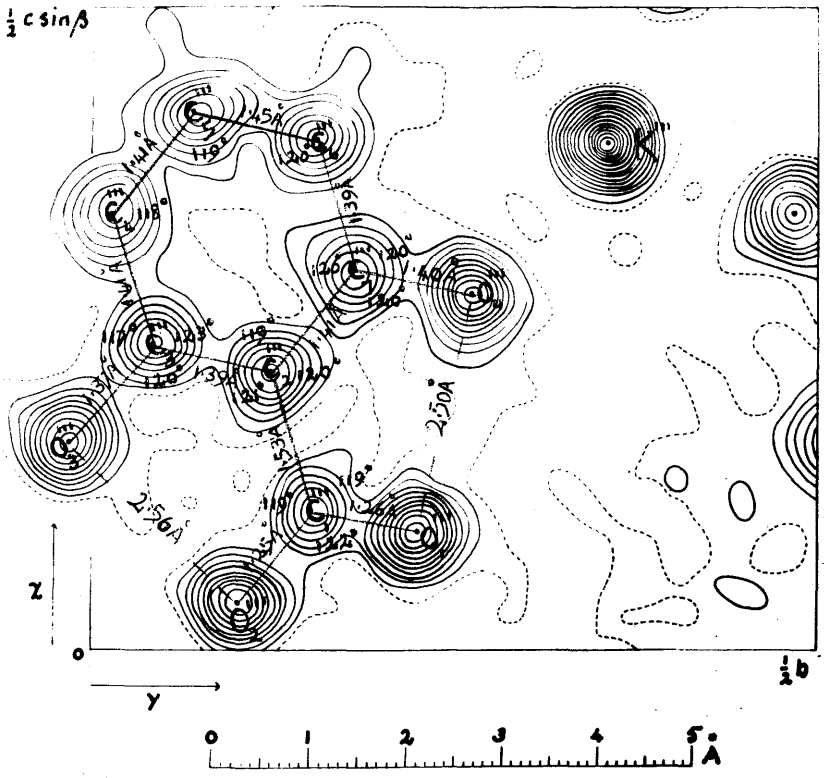


Fig. VIII

Final electron-density projection on (100) plane of potassium salt.

Contour-line scale 1 electron per sq. Å except in potassium ion where the odd contour-lines have been omitted.

Line of unit electron density broken.

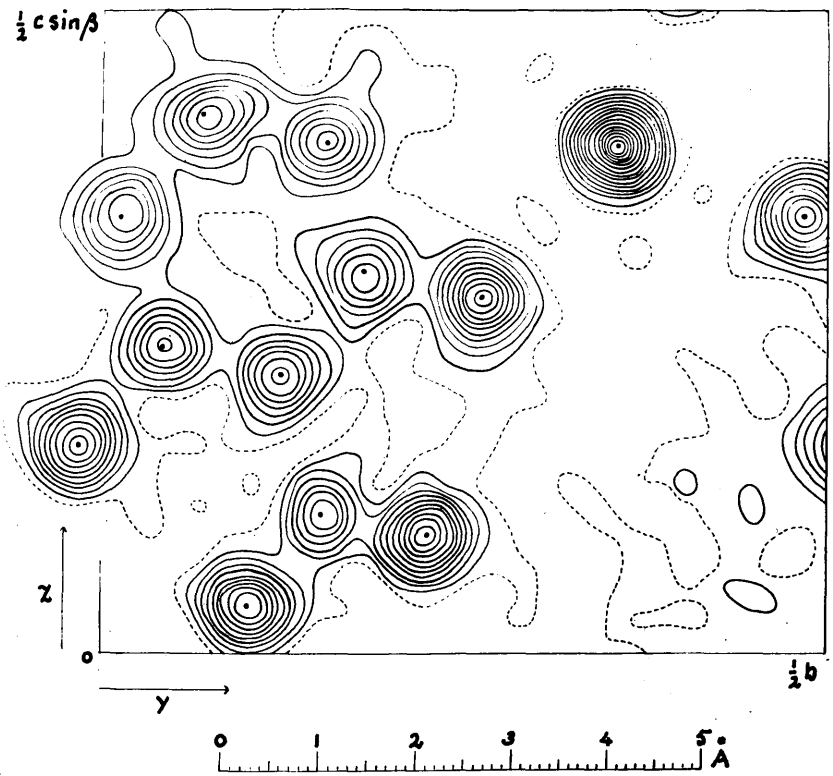


Fig. VIII

Final electron-density projection on (100) plane of potassium salt.

Contour-line scale 1 electron per sq. Å except in potassium ion where the odd contour-lines have been omitted.

Line of unit electron density broken.

discrepancies. It is now clear that errors in co-ordinates and $F_{obs} - F_{calc}$ discrepancies have been transferred to scattering curves, thus applying a very variable temperature factor. The stubborn irregularity of the benzene ring can now be explained. It is interesting to note that although the (100) electron-density map is much improved, the replacement of the empirical scattering curves has produced relatively little change in the co-ordinates and surprisingly few changes of sign. (This was also noticed by Abrahams and Robertson).[97]

The discrepancy in the hk0 zone is still fairly high and the possibility of a two-fold ambiguity such as occurred in the analysis of p-nitroaniline[98] was considered. It would be possible in the h0l zone to choose a false origin lying on a two-fold screw axis rather than a centre of symmetry. Such a change of origin would only affect the hk0 structure factors when h is odd, the 0kl structure factors when l is odd and the h0l structure factors not at all. As the discrepancy in the 0kl zone is quite reasonable for this type of salt containing a heavy ion, and lower in any case than that for the h0l reflections, this possibility seemed unlikely: discrepancies were however calculated for the appropriate groups of structure factors in the hk0 and h0l zones and gave no evidence of the origin being shifted.

[Table II next page

Table II

Stages in the Refinement of the Okl zone

Theoretical no. of Okl spectra = 263

	No.of terms observed	Terms included	Terms with wrong sign	R
Fourier Synthesis I (Vand)	118	50		
II "	"	59	0	57%
III	"	96	16	46%
IV	"	104	12	39.1%
Alteration of potassium scattering curve (Table VIII, line 5)				37.6%
V	"	111	10	26.5%
VI	"	112	3	24%
("Difference") Fourier Synthesis VII - 72 terms - co-ordinate shifts				19.8%
Replacement of C and O scattering curves by $\overline{CO}$ scattering curve using McWeeny data (Table VIII, line 7)				17.6%
Modification of potassium scattering curve (Table VIII, line 8)				17.9%
Modification of all scattering curves according to Speakman's method (Table VIII, lines 9, 10 and 11)				17.2%
Alteration of benzene ring				16.8%
Inclusion of far out reflections				19.9%
Fourier Synthesis VIII	179	168	5	16.0%
IX	"	177	8	14.9%
X ('Booth')	"	172	2	13.9%
('Difference') Fourier Synthesis XI - 135 terms - different temperature factor applied to C scattering curve				15.8%
Different temperature factor applied to O scattering curve				15.7%
Replacement of empirical scattering curves by theoretical scattering curves (Table VIII, lines 12,13 and 14) with applied temperature factor using Berghuis data B_K, B_O and $B_C = 2.4$				11.5%
('Difference') Fourier Synthesis XII - 148 terms - modification of temperature factors, $B_K = 3$, $B_O = 2.4$ and $B_C = 3$ (Table VIII, lines 15, 16 and 17).				9.4%
Fourier Synthesis XIII	179	179	-	-

4. Co-ordinates and Molecular Dimensions.

The atoms of the molecules are numbered as indicated in fig.IX. The co-ordinates of the atoms of the molecule, referred to the unit cell axes with origin on the centre of symmetry and to orthogonal axes, are given in Table III. The co-ordinates of the oxygen atoms surrounding K^1 are also listed.

To convert the x and z co-ordinates found into rectangular co-ordinates, x' and z', the following equations were used:-

$$x' = x - z \cos\beta$$

$$z' = z \sin\beta$$

The rectangular co-ordinates, bond lengths and angles were confirmed on Deuce using a programme developed by Dr. J. C. Speakman.

(Table III next page)

TABLE III

FINAL ATOMIC CO-ORDINATES x,x',y,z and z' in Å

(for numbering of atoms see Fig.IX)

Atom	x/a	x	x'	y/b	y	z/c	z	z'
K^1	0.0254	0.100	-1.805	0.1457	2.200	0.8933	11.943	11.793
O_1^1	0.3840	1.513	0.251	0.2765	4.175	0.5915	7.908	7.807
O_2^1	0.1227	0.483	0.659	0.3992	6.028	0.5358	7.164	7.072
O_3^1	-0.0300	-0.118	1.528	0.5153	7.781	0.6608	8.835	8.722
O_4^1	0.5040	1.986	0.331	0.2385	3.601	0.7760	10.375	10.242
C_1^1	0.2412	0.950	0.344	0.3485	5.262	0.6070	8.116	8.012
C_2^1	0.2323	0.915	0.612	0.3773	5.697	0.7162	9.576	9.453
C_3^1	0.0957	0.377	1.196	0.4583	6.920	0.7377	9.863	9.737
C_4^1	0.0825	0.325	1.461	0.4875	7.361	0.8375	11.197	11.054
C_5^1	0.2148	0.846	1.112	0.4312	6.511	0.9180	12.274	12.116
C_6^1	0.3583	1.412	0.500	0.3463	5.229	0.8962	11.982	11.829
C_7^1	0.3651	1.438	0.261	0.3208	4.844	0.7968	10.653	10.517
O_4^1	0.5040	1.986	0.331	0.2385	3.601	0.7760	10.375	10.242
O_3^{IV}	0.5030	2.088	0.298	0.0153	0.231	0.8392	11.220	11.076
O_2^{III}	0.6227	2.453	0.244	0.1008	1.522	1.0358	13.849	13.671
O_1^{III}	0.8840	3.483	1.155	0.2235	3.375	1.0915	14.593	14.406
$O_4^1\downarrow$	-0.4960	-1.954	-3.609	0.2385	3.601	0.7760	10.375	10.242
$O_3^{IV}\downarrow$	-0.4700	-1.852	-3.642	0.0153	0.231	0.8392	11.220	11.076
$O_2^{III}\downarrow$	-0.3773	-1.487	-3.696	0.1008	1.522	1.0358	13.849	13.671
$O_1^{III}\downarrow$	-0.1160	-0.457	-2.785	0.2235	3.375	1.0915	14.593	14.406

TABLE IV

FINAL BOND LENGTHS AND DISTANCES.

(see fig. IX for numbering)

$C_1 - O_1$	1.256 Å	$\angle O_1 - C_1 - O_2$	121.74°
$C_1 - O_2$	1.252 Å	$\angle O_1 - C_1 - C_2$	118.86°
$O_1 \cdots O_2$	2.191 Å	$\angle O_2 - C_1 - C_2$	119.30°
$C_3 - O_3$	1.371 Å	$\angle C_1 - C_2 - C_7$	119.74°
$C_7 - O_4$	1.403 Å	$\angle C_1 - C_2 - C_3$	121.22°
$C_1 - C_2$	1.529 Å	$\angle C_3 - C_2 - C_7$	119.05°
$C_2 - C_3$	1.385 Å	$\angle O_4 - C_7 - C_2$	119.59°
$C_2 - C_7$	1.408 Å	$\angle O_3 - C_3 - C_2$	120.31°
$C_3 - C_4$	1.414 Å	$\angle O_4 - C_7 - C_6$	120.20°
$C_4 - C_5$	1.405 Å	$\angle C_2 - C_7 - C_6$	120.20°
$C_5 - C_6$	1.449 Å	$\angle O_3 - C_3 - C_4$	116.65°
$C_6 - C_7$	1.388 Å	$\angle C_2 - C_3 - C_4$	123.04°
$O_1 \cdots H - O_4$	2.503 Å	$\angle C_7 - C_6 - C_5$	120.38°
$O_2 \cdots H - O_3$	2.559 Å	$\angle C_5 - C_4 - C_3$	117.98°
$C_3 \cdots C_7$	2.407 Å		
$C_4 \cdots C_6$	2.464 Å		
$C_2 \cdots C_5$	2.829 Å		

TABLE Contd.

K-O AND O---O DISTANCES

$K^{1}-O_{4}^{1}$	2.987 Å	$O_{4}^{1}---O_{3}^{IV}$	3.472 Å
$K^{1}-O_{3}^{IV}$	2.968 Å	$O_{4}^{1}---O_{2}^{III}$	4.011 Å
$K^{1}-O_{2}^{III}$	2.863 Å	$O_{4}^{1}---O_{1}^{III}$	4.251 Å
$K^{1}---O_{1}^{III}$	4.121 Å	$O_{4}^{1}---O_{1}^{III}\downarrow$	5.206 Å
$K^{1}-O_{4}^{1}\downarrow$	2.760 Å	$O_{3}^{IV}---O_{2}^{III}$	2.899 Å
$K^{1}-O_{3}^{IV}\downarrow$	2.786 Å	$O_{3}^{IV}---O_{1}^{III}$	4.659 Å
$K^{1}-O_{2}^{III}\downarrow$	2.752 Å	$O_{2}^{III}---O_{1}^{III}$	2.191 Å
$K^{1}-O_{1}^{III}\downarrow$	3.030 Å	$O_{2}^{III}---O_{1}^{III}\downarrow$	3.626 Å
		$O_{1}^{III}\downarrow---O_{4}^{1}\downarrow$	4.251 Å
		$O_{1}^{III}\downarrow---O_{3}^{IV}\downarrow$	4.659 Å

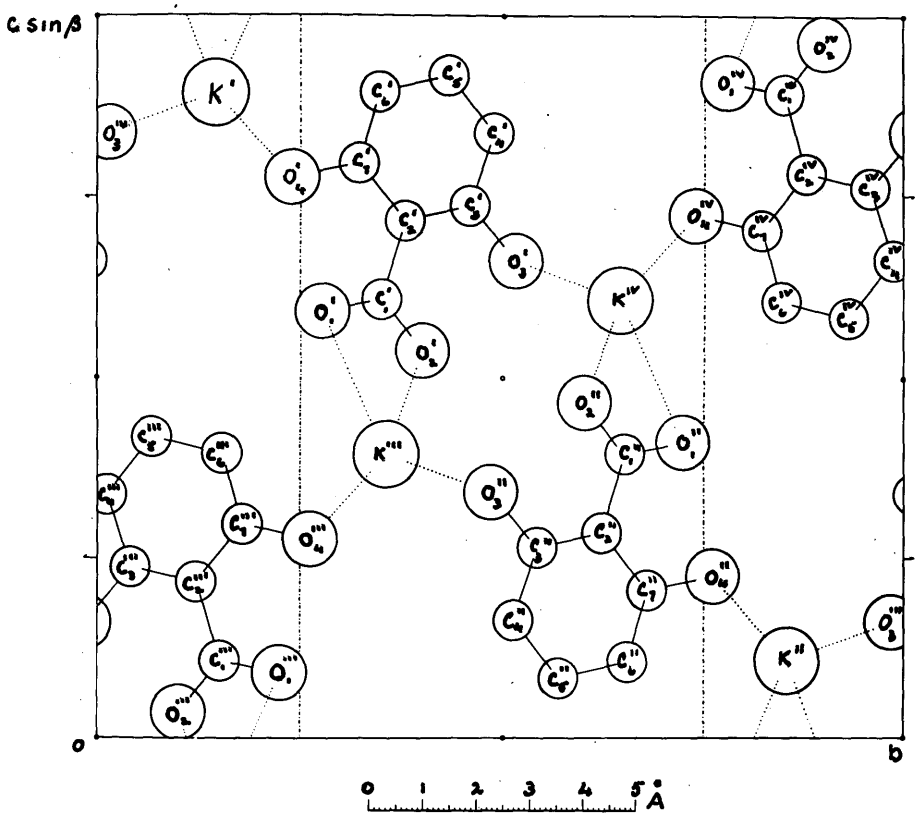


Fig. IX

Numbering and arrangement of atoms on (100) projection of potassium salt based on fig. VIII.

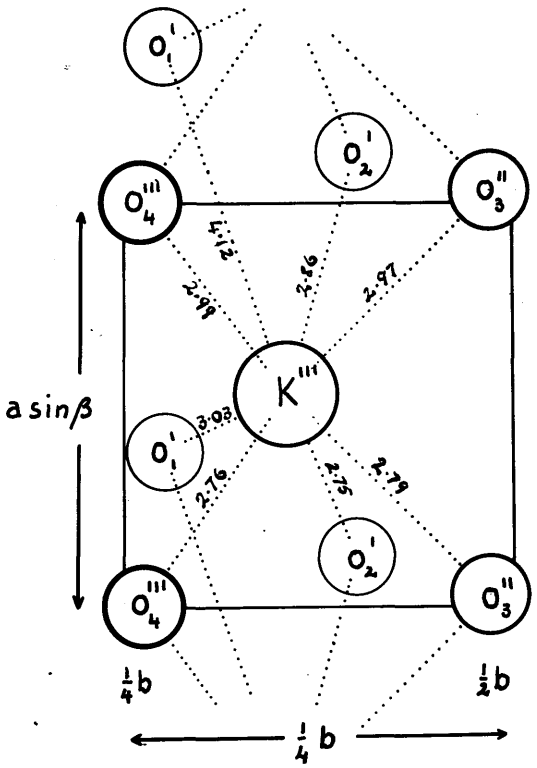


Fig. Xa

.Environment of potassium ion as seen looking down the c axis from the origin. The order of height of the atoms is O_4, O_3, K^+, $O_2$and O_1 as indicated by the line thickness. The distances are in Angstrom units.

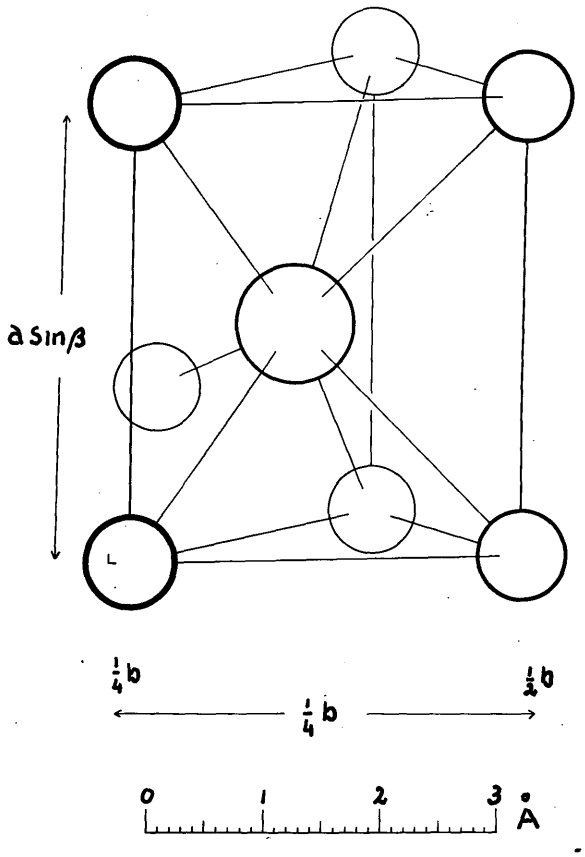


Fig Xb

As Fig. Xa showing prismatic arrangement of oxygen atoms round the potassium ion.

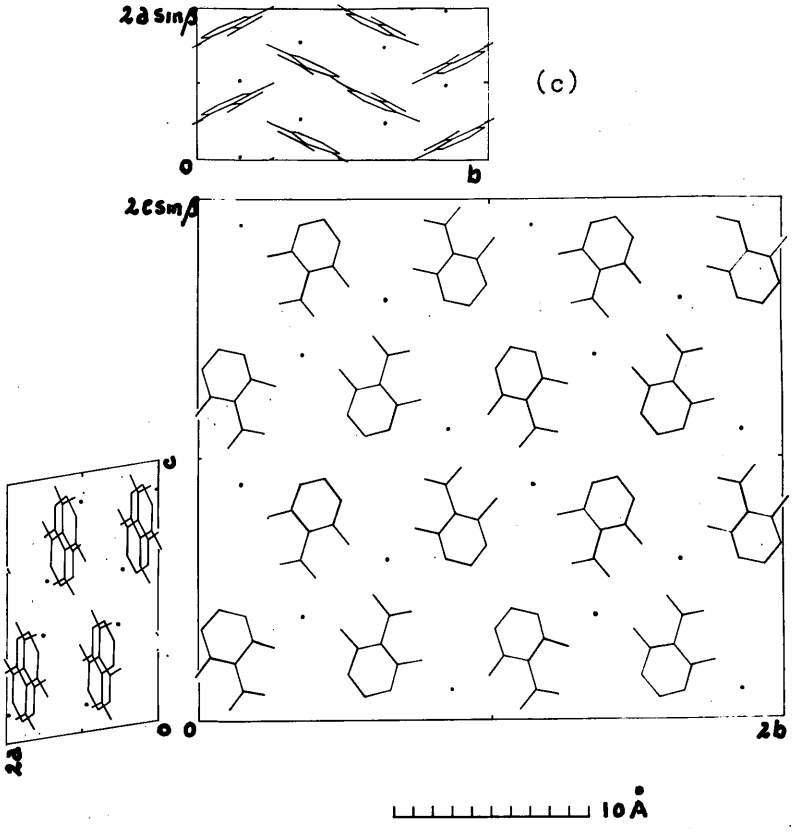


Fig. XI

Projections of the structure of potassium 2:6-dihydroxy benzoate on to

(a) the (100) plane

(b) the (010) plane

(c) the (001) plane

The positions of the potassium ions are indicated by dots.

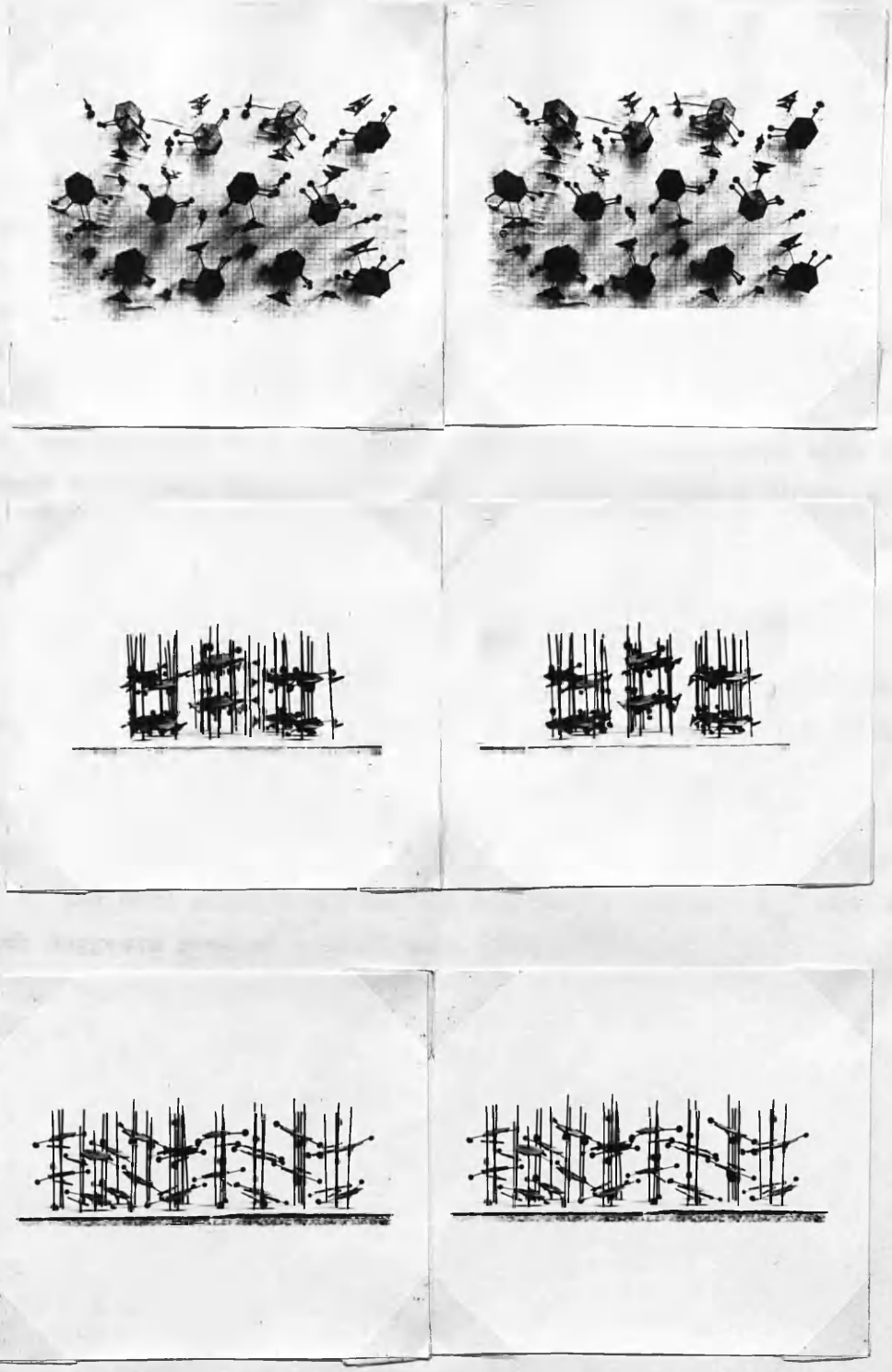


Fig. XII. Stereoscopic photographs of a molecular paper model taken approximately parallel to (a) the a axis, (b) the b axis and (c) the c axis.

5. Accuracy and Significance of the Results.

The accuracy of the structure and the significance of the results can be assessed after the methods put forward by Cruickshank[99,100]. There are three sources of error in electron-density maps, these are errors in the estimated intensities, errors due to a finite series of (hkl) values, along with errors in their subsequent correction and computational errors. After the termination of series errors have been corrected, and assuming that any errors are small in comparison with the inter-atomic distances, the random errors remaining follow a Gaussian probability distribution, i.e. the probability that any particular error lies between x and dx is $\frac{1}{(2\pi\sigma^2)^{\frac{1}{2}}} e^{-x^2/2\sigma^2} dx$; σ is the standard deviation of the error.

If S_o is the estimated standard deviation of a bond length (which may differ from the true value), l_o the estimated bond length and λ_o the probable true value: then, $t_o = (l_o - \lambda_o)/S_o$. The probability that $|t| \geq |t_o|$ due to chance is taken as P and this can be found from the distribution. Within limits, the smaller the value of P the more significant is the difference between l_o and λ_o. Cruickshank suggests several significance levels[99].

If $P > 5\%$ the difference is not significant

$5\% > P \geq 1\%$ " " " possibly significant

$1\% > P \geq .1\%$ " " " significant

$.1\% > P$ " " " highly significant

When $P = .05$ $t_o = 1.96$

$P = .01$ $t_o = 2.576$

$P = .001$ $t_o = 3.291$

Thus two bond lengths may be compared and $t_o = \frac{(l_1 - l_2)}{(S_1^2 + S_2^2)^{\frac{1}{2}}}$, where l_1 and l_2 are the experimentally determined bond lengths and S_1 and S_2 their estimated standard deviations.

The standard deviations in the atomic co-ordinates, σx, σy and σz, derived from well resolved projections, can be calculated by Cruickshank's method[99] after the errors due to termination of series have been corrected.

$$\sigma x = 1/A.2\pi/a.[\sum h^2(\Delta F)^2]^{1/2} \Big/ \partial^2\rho/\partial x^2$$

A is the projected area of the cell,

ΔF is $|F_{obs}| - |F_{calc}|$, where $|F_{obs}|$ and $|F_{calc}|$ are the observed and calculated structure amplitudes,

$\partial^2\rho/\partial x^2$ is the curvature of the electron density peak at the centre of the atom, and $\sum$ indicates a summation over all observed planes. Near an atomic centre the central curvature can be assumed to be

$$\rho = \rho_0 \exp(-Pr^2);$$

ρ is the electron density at a distance r from the centre of the atom,

ρ_0 is the density at the centre of the atom, and P is a constant.

At the centre of the peak

$$\partial^2\rho/\partial x^2 = -2P\rho_0$$

In order to obtain this value, graphs of $\log\rho$ against r^2 were drawn up for potassium, oxygen and carbon atoms using the values obtained from the final electron-density projection on the (100) plane. Average values of P and ρ_0 were thus obtained and hence the central curvatures.

The (010) and (001) projections do not show all of the atoms well resolved and no independent estimate of σx has been made.

The radial error of position σr can be taken as $\sqrt{(\sigma x^2 + \sigma y^2 + \sigma z^2)/3}$. σx has been assumed to be about twice as great as the other co-ordinate standard deviations. This may be an over-estimate but, as it is supposed that, in normal cases, the standard deviations calculated by Cruickshank's method are an under-estimate, it will help to compensate for that.

The standard deviation of a C-C bond, for example, is $\sqrt{2}\ \sigma r\ (C)$ and of the mean benzene ring bond is $1/\sqrt{6}\ \sigma\ r\ (C)$.

The standard deviation of bond angles were calculated according to Cruickshank's formula.[100]

As the number of observations is fairly large compared with the number of unknown parameters, it has not been considered necessary to modify the standard deviations by any further factor as recommended by Cruickshank[101].

The co-ordinate standard deviations obtained are

	σy	σz
Potassium	.00333	.00300
Oxygen	.01231	.01107
Carbon	.01609	.01448

and the radial errors of position are

	σr
Potassium	.00448
Oxygen	.0165
Carbon	.0216

The standard deviations of the bond lengths are

σ C-C = .0305 Å

σ mean benzene ring bond = .00882

σ C-O = .0272

σ O-O = .0233

σ K-O = .0172

and the standard deviations of angles are

$\sigma\ C_3C_2C_7 = 1.46^\circ$

$\sigma\ C_2C_7O_4 = 1.40^\circ$

$\sigma\ O_2C_1O_1 = 1.50^\circ$

The standard deviation of the electron density

$\sigma\rho$ = .097 e/A^2 for the Okl projection.

6. Discussion

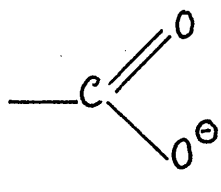
(References are made to the numbered diagram in fig. IX, to the diagrammatic projections in fig XIa, b and c, to photographs of a paper model taken in three directions, fig XIIa, b and c, and to the diagram of the potassium environment in fig. X).

The original purpose of this research was to determine the nature of the hydrogen bonding: this has been found to be intra-molecular and two such bonds exist in each molecule. As expected, however, when the investigation turned to the potassium salt no hydrogen atoms have been resolved. (These would have shown up, if at all, on a difference map and from the final difference map no speculation on hydrogen positions could be justified). However the presence of two internal hydrogen bonds can be inferred with certainty from the distances $O_1 - O_4$ and $O_2 - O_3$ which are 2.50 and 2.56 Å respectively (see fig. IX) and from the fact that there is no evidence of inter-molecular hydrogen bonding: from the C-O-O angles (involving the hydrogen bonded oxygens) which are only of the order of 90°, the hydrogen atoms cannot lie on the line of centres of the oxygen atoms. (Cf. Cochran's values for salicylic acid[22]). The closest inter-molecular oxygen to oxygen approach distance is 2.9 Å between O_2^1 and O_3'' (which are bonded to a common potassium ion) and is so much greater than the intra-molecular distance $O_3'' - O_2''$, which involves the same phenolic oxygen, that an inter-molecular hydrogen bond must be discounted. (In zinc salicylate dihydrate[102] the phenolic oxygen O_3 does form both an inter- and an intra-molecular hydrogen-bond, but the former involves the hydrogen of an adjacent water molecule).

The distances observed here, 2.50 and 2.56 Å agree well with the accepted values for a short hydrogen bond. The most reliable estimate of a comparable hydrogen bond is that of 2.59 Å, made by Cochran for the intra-molecular hydrogen bond in salicylic acid[22]. In this case the hydrogen was located. A less accurate estimate of 2.51 Å is made by Klug and Alexander[102] for the corresponding bond length in zinc salicylate dihydrate. It is probably more interesting and perhaps fairer to compare the distances found in this work with those quoted by Speakman

and Downie[5] in a study of the acid salt ammonium hydrogen disalicylate hydrate, where two different intra-molecular O-H---O bond lengths were determined in the same structure and presumably with the same degree of accuracy. These authors distinguish two salicylate residues - the acid and the anionic residues and quote intra-molecular hydrogen bond lengths of 2.63 and 2.45 Å respectively. The O-H---O bond lengths in this structure fall between these values.

All of the salicylate evidence suggests that the internal hydrogen bond might be expected to be shorter in the anion than in the free acid. This is reasonable because the repulsion of the acidic H is removed and because of the increased mesomeric effect within the carboxyl group itself which can be supposed to have the resonance structures 1), 2) and 3).



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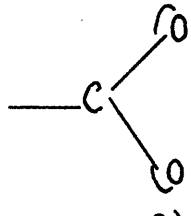
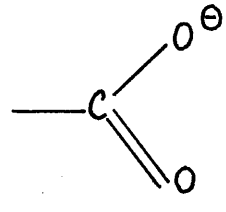


2)



3)

The unperturbed structures 1) and 3) are equivalent in the anion so that the negative change is distributed equally between the oxygen atoms and the energy of mesomerism is therefore greater than in the acid. This is borne out by the bond lengths quoted for the carboxyl group in this structure and in the other structures discussed, (apart from those cited for zinc salicylate which appear to be anomalous); see Table V. This increase in resonance may then extend to the chelate ring to produce a stronger and shorter hydrogen bond. It is not unreasonable that the O-H---O bond length in a dichelated salt should fall midway between the two quoted for ammonium hydrogen disalicylate hydrate, as thus the

Table V

C-O distances within the carboxyl groups of some aromatic acids.

	Å	Å
Potassium 2:6-dihydroxy benzoic acid	1.25	1.26
Potassium hydrogen p-hydroxy benzoate hydrate	1.20	1.29
Salicylic acid	1.24	1.33
Ammonium hydrogen disalicylate hydrate (acid)	1.29	1.34
(anion)	1.27	1.29
Zinc salicylate	1.19	1.26

symmetry of the organic residue is preserved and undue distortion is prevented. (The angles $C_2C_1O_1$ and $C_2C_1O_2$ are both 119° as compared with angles $C_9C_8O_5$ and $C_9C_8O_4$ of the anion in the ammonium acid salt, which are 116° and 120° respectively).

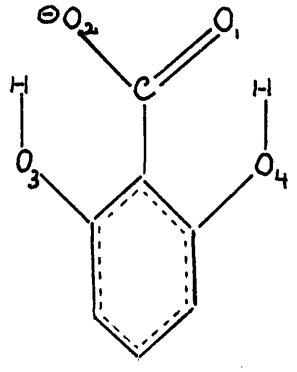
It is possibly significant that the two hydrogen bonds here are not equivalent and this is assumed to be due to the fact that the oxygen O_2 is attached to two potassium ions at distances of 2.75 and 2.86 Å whereas the atom O_1 forms only one bond of length 3.03 Å with the cation.

The packing of the molecules in the crystals is determined by their ionic character, so that the oxygen atoms pack round the cation and the non-polar residues pack together with van der Waals forces which are less specific than the ionic forces. This type of ionic packing is quite usual in salts of organic compounds, viz. potassium benzyl penicillin.[64] In the acid salts studied by Speakman et.al.,[2,3,4,5] the cations also largely determine the packing, but inter-molecular hydrogen bonding is also a factor, particularly in the hydrates. As was found in the acid salts there are no discrete molecules. The complete molecule can be identified in zinc salicylate dihydrate but this is probably occasioned by the

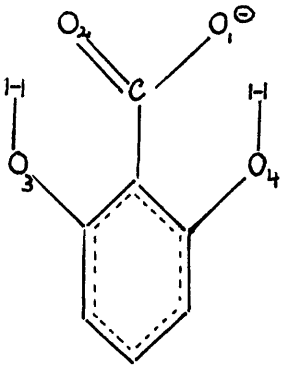
tetrahedral co-ord ination round the zinc atom. Frequently the metal and its adjacent oxygen atoms form an ionic layer as in potassium benzyl penicillin. In the salts potassium hydrogen bisphenylacetate and potassium hydrogen dibenzoate the structure is built up of sheets of potassium and hydrogen atoms and acid residues in such a way that there are two sheets of acid residues followed by one of potassium and hydrogen atoms. In this case the organic residues are co-ordinated round a central metal ion by K-O links in all directions, involving phenolic and carboxylic oxygens. This deviation from the ionic layer structure presumably follows because the phenolic oxygens are involved in the co-ordination sphere, (cf. packing in ammonium hydrogen disalicylate hydrate). Each potassium is attached to six anions each of which in turn is associated with six cations. In projection down the a axis (figs. IX and XIa) each metal ion appears to be surrounded by three organic residues in such a way that six of these pack hexagonally round a central residue to form a "condensed" system. The transform of these large hexagons and of the individual benzene rings is obvious from the weighted reciprocal lattice (appendix 3, fig XIII).

The K^+ ion is surrounded by seven bonded oxygens, six of which are arranged to form a trigonal prism (fig X). This prism is made up of smaller prisms involving the metal ion - these are two triangular prisms and three four-sided prisms, each with the potassium at the apex. The corners of the trigonal prism are formed by one carboxylic and two phenolic oxygens O_2, O_3 and O_4 along with the corresponding oxygens of adjacent unit cells, above or below, so that the height of the prism is the length of the a axis. The potassium ion (K_3 as shown in fig X), is nearer to the base of the prism and the K-O distances to the basal oxygens are ~ 2.8 Å those to the upper oxygens are 2.9 - 3.0 Å. The seventh oxygen O_1 is 3.03 Å from the potassium ion and is added beyond one of the rectangular faces. In the acid salts studied [2,3,4], the potassium has been found bonded to six oxygens and this packing is probably more usual: similar packing to that found here is recorded in potassium benzyl penicillin[64], K_2NbF_7 and K_2TaF_7[103].

The oxygen atoms O_4, O_3 and O_2 are each associated with two potassium ions, the atom O_1 with one. It might have been expected that the metal ion would be equally attracted to both oxygens of the carboxyl group as in potassium caprate[104] and that the phenolic oxygen would be added in later, like the amide oxygens in potassium benzyl penicillin[64]. It is at first surprising that the phenolic oxygens should have an attraction as great as the carboxyl oxygen O_2. In zinc salicylate dihydrate only one of each of the carboxyl oxygens is attracted to the cation and in ammonium hydrogen disalicylate hydrate the phenolic oxygen is also bonded to the NH_4^+ ion. The analogous oxygen of the acid residue is not bonded. (The phenolic oxygen in the zinc salt is not bonded to the cation but as the co-ordination round zinc is quite different, in this case tetrahedral, a comparison is hardly valid). It seems that this effect is due to the shorter hydrogen bond in the anion so that here the ionisable character of the phenolic oxygen is greater and it is not then surprising to find that both phenolic oxygens of the dichelated anion should be attracted to the potassium ion. If this is conceded, the odd packing of the seven oxygen atoms round the potassium must be presumed due to steric reasons which permit the best formation of K-O bonds, as the first condition to be satisfied is that the metal ion should be surrounded by as many electronegative oxygens as possible. It is also possible that the hydrogen of the O_4-H---O_1 bond is closer to O_1 than the corresponding hydrogen to O_2 thus rendering O_1 less electronegative as in structures 4) and 5) below. Of the simple structures 1) to 6) the evidence suggests that for reasons of environment, contributions from structures 2) and 3) may be partially suppressed.



1)



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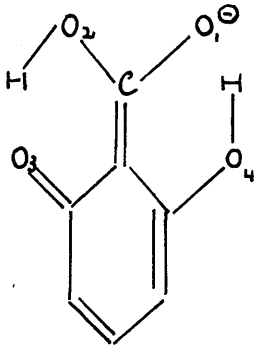
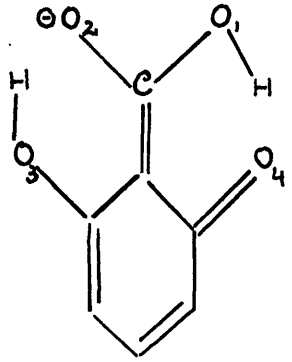
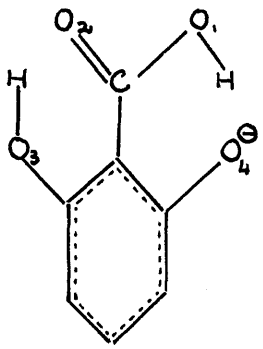


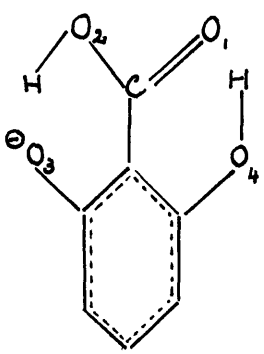
3)



4)



5)



6)

The K-O bond lengths, varying from 2.75 to 3.03 Å, are well within the values previously quoted for bonded potassium and oxygen. Speakman et.al., quote values varying from 2.69 to 3.12 Å in potassium hydrogen bisphenylacetate[2] and 2.7 to 3.1 Å in potassium hydrogen di-p-hydroxy benzoate hydrate[3] and from 2.79 to 2.84 Å in potassium hydrogen dibenzoate[4].

The bond lengths within the organic residue are reasonably consistent with Cochran's values for salicylic acid[22]. The molecule is planar within the limits of experimental error. The bond C_5- C_6 seems unduly long at 1.45 Å but there is no significant difference from the average bond length in the ring of 1.41 Å. The average angle of the ring is 120° and again none of the deviations from this value is significant. The dimensions of the carboxyl group indicate a symmetrical group as would be expected. The C-O_1 and C-O_2 bond lengths, 1.26 and 1.25 Å are equivalent within the limits of experimental error. This feature has already been discussed and results from the cross conjugation of these bonds in the anion. This also accounts in part for the length of the C_1-C_2 bond, 1.53 Å, which is of course significantly different from the value of 1.48 Å observed in salicylic acid (cf. the bond length 1.53 Å for C_1- C_2 in potassium hydrogen dibenzoate[4]). Possibly steric reasons also affect the issue, as in hexamethylbenzene where the C-CH_3 bonds are longer than expected[105] and this is the minimum bond length which will preserve a reasonable distance between the oxygen atoms O_2' and O_3''.

The closest approach distance between atoms not bonded to each other or to a common atom is 3.06 Å between K and C_6.

7. Final Structure Factors.

The final structure factors calculated from the atomic co-ordinates given in Table III are shown in Table VI under $F_{calc.}$ together with the observed structure amplitudes $|F|_{obs}$ which have been scaled by comparison with the calculated values. In the calculation of these structure factors, the theoretical scattering curves of Berghuis et.al.,[96] for potassium, oxygen and carbon were employed, the value of the constant B in the temperature factor being 3, 2.4 and 2.4 respectively. The discrepancies, R, expressed as $\Sigma\left||F|_{obs} - |F|_{calc}\right| / \Sigma|F|_{obs}$, for the (0kl), (h0l) and hk0 zones were 9.4, 14.2 and 20.03% respectively. The reflections $\bar{1}05$, 101, 130 and 120 reflections were considered to suffer from secondary extinction and were not included in the calculation of R.

(Table VI next page

TABLE VI

OBSERVED STRUCTURE AMPLITUDES AND CALCULATED STRUCTURE FACTORS

(a) Potassium 2:6-dihydroxy benzoate:-

hkl	2 sinθ	|Fobs|	Fcalc.	hkl	2 sinθ	|Fobs|	Fcalc.
002	0.23	30.1	-30.4	021	0.23	41.6	-43.3
004	0.47	57.4	-61.3	022	0.31	3.3	- 5.1
006	0.70	59.8	-61.1	023	0.41	12.9	+13.2
008	0.93	18.2	+16.6	024	0.51	<1.5	+ 2.9
0010	1.17	32.0	+30.9	025	0.62	47.3	-43.1
0012	1.40	2.4	+ 1.8	026	0.73	52.1	+49.3
0014	1.63	17.2	-17.0	027	0.84	24.9	-26.4
0016	1.87	22.0	-18.9	028	0.96	5.3	-10.7
				029	1.07	3.8	+ 0.6
011	0.16	54.0	+53.0	0,2,10	1.19	31.5	-33.5
012	0.26	43.0	+42.8	0,2,11	1.30	5.7	+ 2.0
013	0.37	16.7	-15.9	0,2,12	1.42	11.5	+13.1
014	0.48	17.2	-21.8	0,2,13	1.53	8.1	+ 5.2
015	0.60	4.8	- 5.9	0,2,14	1.60	<2.3	+ 1.6
016	0.71	18.2	-16.9	0,2,15	1.77	8.6	- 8.1
017	0.82	2.4	+ 2.3	0,2,16	1.88	2.9	+ 1.3
018	0.94	29.6	-27.5				
019	1.06	16.3	+17.7	031	0.33	57.4	-64.7
0,1,10	1.17	6.2	+10.0	032	0.39	39.7	+39.8
0,1,11	1.29	5.3	- 9.1	033	0.47	5.7	+ 6.3
0,1,12	1.43	9.6	+ 6.1	034	0.56	35.9	+37.4
0,1,13	1.52	8.1	- 7.2	035	0.66	52.6	+57.1
0,1,14	1.64	<2.3	+ 3.2	036	0.76	62.1	-58.8
0,1,15	1.76	14.8	-13.3	037	0.87	6.2	+ 8.8
0,1,16	1.87	4.3	- 5.1	038	0.98	12.9	-11.6
0,1,17	1.99	<.3	- 2.2	039	1.09	28.7	-27.1
				0,3,10	1.21	28.2	-28.4
020	0.20	10.0	- 9.2	0,3,11	1.32	8.1	- 8.3

TABLE Contd.

hkl	2 sinθ	|Fobs|	Fcalc	hkl	2 sinθ	|Fobs|	Fcalc.
0,3,12	1.43	16.7	+14.3	058	1.06	26.8	+25.6
0,3,13	1.55	10.5	+10.5	059	1.17	< 2.4	- 0.9
0,3,14	1.67	< 2.3	+ 3.2	0,5,10	1.27	6.7	- 7.6
0,3,15	1.78	11.5	+11.6	0,5,11	1.38	10.5	+11.4
0,3,16	1.89	5.3	+ 2.4	0,5,12	1.49	20.6	-23.7
				0,5,13	1.60	15.8	+13.5
040	0.41	23.4	-29.6	0,5,14	1.71	< 2.2	+ 2.6
041	0.42	9.1	-10.6	0,5,15	1.83	< 1.9	- 1.1
042	0.47	58.3	-57.5	0,5,16	1.93	9.6	+ 9.9
043	0.54	5.3	- 4.5				
044	0.62	30.6	+27.0	060	0.61	34.4	+38.4
045	0.71	25.8	-25.5	061	0.62	13.9	-15.9
046	0.81	32.0	+30.8	062	0.65	12.9	-14.8
047	0.91	12.9	+ 8.9	063	0.70	33.9	-33.6
048	1.02	15.8	-16.7	064	0.77	60.7	-61.8
049	1.12	11.8	-12.2	065	0.84	< 1.9	+ 1.1
0,4,10	1.23	30.6	-30.1	066	0.93	12.0	+12.6
0,4,11	1.35	3.3	+ 1.3	067	1.02	37.3	+33.8
0,4,12	1.45	19.6	+22.2	068	1.18	14.3	+11.5
0,4,13	1.58	5.7	- 3.1	069	1.22	10.5	+13.9
0,4,14	1.69	15.8	+15.7	0,6,10	1.32	17.2	+14.4
0,4,15	1.80	2.9	+ 1.8	0,6,11	1.42	2.7	- 0.8
0,4,16	1.91	< 1.5	+ .7	0,6,12	1.52	< 2.5	+ 2.4
				0,6,13	1.63	11.5	-11.6
051	0.52	9.1	- 7.8	0,6,14	1.74	14.3	-12.3
052	0.56	40.2	-34.1	0,6,15	1.85	< 1.8	+ 5.8
053	0.62	10.5	-10.7	0,6,16	1.96	< 0.9	+ 0.6
054	0.69	39.2	-34.6				
055	0.78	29.6	-23.2	071	0.72	31.1	+25.9
056	0.86	36.8	+36.6	072	0.75	36.3	+38.1
057	0.96	< 2.2	0.0	073	0.79	22.9	-21.1

TABLE Contd.

hkl	2 sinθ	|Fobs|	Fcalc.	hkl	2 sinθ	|Fobs|	Fcalc.
074	0.85	<1.9	+ 2.1	091	0.92	21.5	+22.8
075	0.92	26.7	-29.0	092	0.94	34.9	+38.3
076	1.0	10.0	+ 3.5	093	0.98	<2.2	+ 5.3
077	1.08	<2.3	+ 5.3	094	1.03	<2.2	+ 3.0
078	1.17	11.0	+12.1	095	1.08	13.4	+10.8
079	1.27	19.6	+14.5	096	1.15	16.7	-18.1
0710	1.36	4.3	- 5.3	097	1.22	13.9	-18.6
0711	1.47	7.6	+ 7.8	098	1.31	<5.5	+ 6.3
0712	1.57	9.1	+ 9.8	099	1.39	4.8	+ 2.0
0713	1.67	9.6	- 9.5	0910	1.48	<2.8	+ 4.9
0714	1.78	<2.0	- 0.8	0911	1.57	<2.4	- 1.4
0715	1.90	<1.7	- 2.4	0912	1.67	10.0	+ 8.9
0716	1.99	<0.3	+ 2.9	0913	1.77	<2.0	+ 0.8
				0914	1.87	<1.7	+ 5.3
080	0.82	45.9	+50.9	0915	1.97	<0.6	- 0.8
081	0.82	3.8	+ 7.9				
082	0.85	12.4	-12.8	0100	1.02	34.4	-31.8
083	0.89	54.5	+52.8	0101	1.03	10.5	+10.8
084	0.94	15.8	-13.7	0102	1.04	8.6	+ 5.8
085	1.00	<2.2	+ 0.1	0103	1.08	<2.2	+ 4.3
086	1.07	<2.3	+ 1.3	0104	1.12	24.4	+23.3
087	1.15	<2.4	- 2.2	0105	1.17	<2.4	- 6.1
088	1.24	8.1	+ 9.5	0106	1.23	37.3	+39.7
089	1.33	9.1	- 3.2	0107	1.30	<5.4	+ 1.2
0810	1.42	5.7	+ 2.2	0108	1.38	22.5	-23.2
0811	1.52	4.8	+ 7.2	0109	1.46	<2.7	- 1.9
0812	1.61	<2.4	- 1.8	01010	1.55	23.4	-23.7
0813	1.72	7.2	+ 8.3	01011	1.63	<2.4	+ 3.0
0814	1.83	<1.9	- 5.9	01012	1.72	<2.2	- 0.2
0815	1.93	<1.4	0.0	01013	1.82	<1.9	- 1.3

TABLE Contd.

hkl	2 sinθ	Fobs.	Fcalc.	hkl	2 sinθ	Fobs.	Fcalc.
01914	1.92	10.5	+ 9.3	01212	1.85	<1.8	+ 6.5
0111	1.13	21.5	-20.8	0131	1.33	14.3	-11.9
0112	1.14	15.3	-19.0	0132	1.34	<5.4	+ 2.5
0113	1.17	22.9	+25.3	0133	1.36	5.3	- 8.2
0114	1.21	17.2	-18.4	0134	1.40	22.0	-24.1
0115	1.26	15.3	+14.5	0135	1.45	16.3	-14.9
0116	1.32	6.2	- 6.2	0136	1.49	9.6	+ 7.9
0117	1.38	17.2	+17.7	0137	1.56	<2.5	- 0.8
0118	1.46	24.4	+25.2	0138	1.62	<2.6	- 1.1
0119	1.53	25.3	-26.1	0139	1.69	11.0	+11.9
01110	1.62	10.0	-11.7	01310	1.76	3.8	- 4.3
01111	1.70	<2.2	- 5.3	01311	1.83	<1.8	+ 5.7
01112	1.78	7.6	- 5.8	01312	1.91	9.1	- 9.1
01113	1.88	<1.7	- 0.9				
01114	1.98	<0.5	- 1.0	0140	1.43	15.8	+16.7
				0141	1.43	6.2	+ 4.7
0120	1.23	<0.6	+10.7	0142	1.44	13.9	+12.4
0121	1.23	15.3	-11.7	0143	1.47	17.2	-15.6
0122	1.24	<2.5	+ 2.0	0144	1.50	30.1	-34.0
0123	1.27	<5.4	- 3.6	0145	1.54	<5.4	+ 2.2
0124	1.31	7.6	- 8.1	0146	1.58	12.0	-12.9
0125	1.35	5.7	- 7.3	0147	1.64	<2.3	+ 0.7
0126	1.41	3.8	+ 6.7	0148	1.70	<2.2	+ 6.8
0127	1.47	<2.7	+ 0.8	0149	1.77	<2.0	+ 0.9
0128	1.54	<2.5	- 6.7	01410	1.84	13.9	+14.0
0129	1.61	<2.4	- 4.1	01411	1.91	<1.5	- 2.0
01210	1.69	<0.4	+ 0.7	01412	1.98	<0.4	+ 8.5
01211	1.77	12.9	-13.6				

TABLE Contd.

hkl	2 sinθ	|Fobs.|	Fcalc.	hkl	2 sinθ	|Fobs.|	Fcalc.
0151	1.51	<2.4	- 5.3	0177	1.91	<1.5	- 2.6
0152	1.54	16.7	+20.6	0178	1.96	< 0.9	+ 1.0
0153	1.57	4.3	- 4.7				
0154	1.60	<2.4	- 2.3	0180	1.84	4.3	- 2.3
0155	1.64	<2.4	- 5.3	0181	1.84	<1.9	+ 0.3
0156	1.68	9.1	- 8.2	0182	1.85	<1.7	- 0.2
0157	1.73	<2.2	+ 4.9	0183	1.86	<1.8	- 4.2
0158	1.79	<2.0	+ 0.2	0184	1.89	4.3	+ 4.3
0159	1.85	<1.8	+ 2.7	0185	1.92	2.4	+ 3.9
01510	1.92	<1.5	+ 1.0	0186	1.96	<0.3	+ 3.4
01511	1.99	<0.4	+ 3.7				
				0191	1.94	<2.7	+ 4.5
0160	1.63	11.0	-10.6	0192	1.95	<1.1	- 8.8
0161	1.63	9.6	+ 9.9	0193	1.97	<0.8	+ 4.2
0162	1.65	11.0	-11.3	0194	1.99	<0.4	- 1.9
0163	1.67	6.2	+ 9.5				
0164	1.70	12.0	+11.3	110	0.41	21.4	-28.0
0165	1.74	2.9	+ 1.9	120	0.44	68.5	+88.1
0166	1.78	9.6	+ 8.7	130	0.50	93.0	-109.6
0167	1.82	<1.9	- 4.4	140	0.57	7.3	+ 2.3
0168	1.88	10.0	- 7.8	150	0.64	6.7	- 8.8
0169	1.94	<1.1	+ 0.8	160	0.73	9.2	+ 6.8
				170	0.82	26.3	+26.0
0171	1.73	10.5	-10.5	180	0.90	<3.3	- 2.3
0172	1.75	13.4	+15.3	190	1.03	17.5	-29.7
0173	1.77	<2.0	+ 4.0	1100	1.10	5.5	+ 5.9
0174	1.79	<2.0	+ 2.5	1110	1.19	20.2	-24.0
0175	1.83	12.0	+10.8	1120	1.28	<4.4	- 1.2
0176	1.86	<1.8	+ 2.2	1130	1.39	17.7	+14.9

TABLE Contd.

hkl	2 sinθ	|Fobs.|	Fcalc.	hkl	2 sinθ	|Fobs.|	Fcalc.
1,14,0	1.49	5.5	+ 6.2	370	1.39	16.5	+12.3
1,15,0	1.58	11.6	+ 9.1	380	1.44	11.0	- 7.9
1,16,0	1.68	5.5	- 3.0	390	1.50	7.3	- 9.3
1,17,0	1.78	10.4	-12.4	3,10,0	1.57	4.9	+ 4.3
1,18,0	1.88	2.4	+ 1.8	3,11,0	1.64	9.8	- 5.5
1,19,0	1.98	<1.9	+ 0.4	3,12,0	1.71	16.5	+13.7
				3,13,0	1.78	<3.6	+ 0.2
200	0.79	46.5	+47.8	3,14,0	1.86	<3.3	+ 7.2
210	0.79	<3.5	+ 2.8	3,15,0	1.94	<2.4	+ 7.5
220	0.82	9.8	- 5.9				
230	0.85	37.9	-45.0	400	1.58	8.6	+ 8.2
240	0.89	14.1	+19.4	410	1.58	9.8	- 7.7
250	0.94	<3.6	- 4.9	420	1.60	<4.3	- 2.8
260	1.0	19.0	+18.9	430	1.61	7.3	- 3.6
270	1.06	<4.0	+ 4.2	440	1.63	9.8	- 6.4
280	1.14	21.4	+26.1	450	1.66	9.2	+ 5.4
290	1.21	16.5	-10.2	460	1.69	<4.0	+ 5.5
2,11,0	1.38	6.7	- 8.0	470	1.73	<3.7	- 6.7
2,12,0	1.46	4.3	+ 5.3	480	1.78	9.2	+10.7
2,13,0	1.54	<4.3	- 4.3	490	1.83	8.6	-10.5
2,14,0	1.64	6.7	+ 9.1	4,10,0	1.88	8.0	-12.1
2,15,0	1.72	<3.6	- 1.7	4,11,0	1.94	<2.3	- 0.9
2,16,0	1.81	7.3	- 5.3	4,12,0	2.0	<1.7	+ 2.6
2,17,0	1.91	2.6	- 3.1				
2,18,0	1.98	<1.9	- 0.8	10,1,5	1.84	<2.5	+ 2.9
				10,1,3	1.61	<3.3	- 3.4
310	1.19	11.0	+10.2	10,1,1	1.38	36.4	+38.5
320	1.20	12.2	- 5.7	109	1.17	6.1	+ 1.4
330	1.23	12.9	-14.4	107	0.95	10.4	-12.0
340	1.26	8.0	+ 5.9	105	0.75	42.4	-53.8
350	1.29	14.7	-25.1	103	0.56	33.3	+41.4
360	1.34	26.3	+21.4	101	0.42	72.5	+112.2

TABLE Contd.

hkl	2 sinθ	|Fobs.|	Fcalc.	hkl	2 sinθ	|Fobs.|	Fcalc.
$\bar{1}01$	0.40	63.8	-64.9	301	1.23	25.8	+25.4
$\bar{1}03$	0.49	44.4	-47.8	$\bar{3}01$	1.17	<3.3	+ 5.3
$\bar{1}05$	0.66	76.5	-116.0	$\bar{3}03$	1.19	15.4	-11.5
$\bar{1}07$	0.85	33.8	+32.6	$\bar{3}05$	1.24	20.5	-21.9
$\bar{1}09$	1.06	34.6	+31.4	$\bar{3}07$	1.33	6.6	+ 6.7
$\bar{1}0,11$	1.28	11.9	+14.1	$\bar{3}09$	1.46	15.9	+14.0
$\bar{1}0,13$	1.51	19.4	-20.2	$\bar{3}0,11$	1.61	<3.3	- 0.8
$\bar{1}0,15$	1.73	8.8	- 5.7	$\bar{3}0,13$	1.79	24.5	-26.8
$\bar{1}0,17$	1.96	<1.7	+ 8.6	$\bar{3}0,15$	1.96	<6.6	+ 1.1
20,14	1.90	6.3	- 1.1	408	1.93	13.9	+ 3.6
20,12	1.69	4.0	+ 4.4	406	1.81	6.8	-10.3
20,10	1.49	9.3	-14.0	404	1.71	12.9	-11.5
208	1.30	6.8	+ 8.0	402	1.63	<3.3	+ 8.8
206	1.13	26.3	-25.0	$\bar{4}02$	1.56	16.7	-22.2
204	0.97	12.4	-15.2	$\bar{4}04$	1.58	15.9	- 7.2
202	0.85	8.1	+ 4.1	$\bar{4}06$	1.64	<3.3	+ 1.9
$\bar{2}02$	0.79	21.7	-32.5	$\bar{4}08$	1.72	13.4	+ 9.4
$\bar{2}04$	0.86	24.7	-25.4	$\bar{4}0,10$	1.82	7.8	+ 5.1
$\bar{2}06$	0.98	28.3	+28.6	$\bar{4}0,12$	1.95	<1.7	- 6.9
$\bar{2}08$	1.13	16.2	+20.5				
$\bar{2}0,10$	1.31	18.7	+19.0	501	1.99	<1.4	- 3.0
$\bar{2}0,12$	1.51	3.5	+ 2.0	$\bar{5}01$	1.94	<1.8	+ 2.4
$\bar{2}0,14$	1.71	22.5	-19.0	$\bar{5}03$	1.94	<1.8	+ 1.5
$\bar{2}0,16$	1.93	<7.5	- 5.6	$\bar{5}05$	1.97	<1.6	- 4.6
30,11	1.86	8.6	+ 5.5				
309	1.68	15.9	+10.5				
307	1.53	9.6	- 3.6				
305	1.39	10.9	- 9.6				
303	1.29	11.9	+11.5				

TABLE Contd.

(b) Rubidium 2:6-dihydroxy benzoate:-

hkl	2 sinθ	Fobs.	hkl	2 sinθ	Fobs.
002	0.23	29.2	031	0.32	91.4
004	0.48	108.0	032	0.38	78.3
006	0.71	85.2	033	0.45	45.8
008	0.94	59.0	034	0.55	49.3
0010	1.18	57.5	035	0.66	119.0
0014	1.65	44.6	036	0.76	88.0
			038	0.98	31.6
011	0.16	78.4	039	1.09	81.5
012	0.27	90.6	0310	1.20	22.4
013	0.36	48.4	0312	1.42	26.7
015	0.60	46.8	0313	1.53	27.9
016	0.71	64.5			
018	0.94	61.5	040	0.39	80.4
019	1.09	47.4	041	0.40	38.0
0110	1.18	55.4	042	0.46	74.7
0112	1.39	33.7	043	0.54	50.8
0113	1.51	35.6	044	0.61	100.0
			045	0.69	21.6
020	0.21	35.2	046	0.80	71.6
021	0.24	15.9	047	0.90	39.4
022	0.30	8.7	048	1.01	53.4
023	0.40	77.4	049	1.12	22.0
024	0.50	19.4	0410	1.23	65.4
025	0.62	92.0	0411	1.33	10.0
026	0.72	78.3	0412	1.45	31.6
027	0.83	89.2	0413	1.55	11.7
028	0.94	24.8			
0210	1.18	48.6	051	0.52	19.1
0211	1.28	37.9	052	0.56	10.6
0212	1.40	17.0	054	0.69	0.8
0213	1.51	17.7	055	0.77	30.4

TABLE Contd.

hkl	2 sinθ	Fobs.	hkl	2 sinθ	Fobs.
056	0.85	97.0	081	0.81	44.7
058	1.06	65.5	082	0.84	24.8
059	1.16	14.4	083	0.88	102.0
0510	1.26	34.2	084	0.92	53.5
0511	1.37	25.1	087	1.14	40.5
0512	1.48	44.7	088	1.23	35.2
0513	1.60	19.8	089	1.32	15.3
			0811	1.50	28.3
060	0.61	73.6			
061	0.62	61.2	091	0.91	14.1
062	0.65	8.6	092	0.93	96.0
063	0.70	70.7	094	1.01	26.1
064	0.76	128.9	095	1.08	36.3
065	0.83	15.9	096	1.15	51.7
067	1.01	80.6	097	1.21	11.5
068	1.11	40.7	098	1.29	13.9
0610	1.30	48.2	099	1.38	9.7
0611	1.40	23.7	0910	1.46	27.2
0614	1.70	31.6	0912	1.66	31.6
071	0.71	74.5	0100	1.00	78.0
072	0.73	52.6	0101	1.01	13.0
073	0.79	54.7	0103	1.06	7.1
075	0.90	83.0	0104	1.15	58.4
077	1.07	13.4	0106	1.22	52.5
079	1.26	64.0	0108	1.37	53.5
0711	1.45	18.3	0109	1.44	9.4
0712	1.55	30.0	01010	1.54	44.2
1713	1.67	31.6			
			0111	1.11	41.8
080	0.81	81.4	0112	1.13	46.0

TABLE Contd.

hkl	2 sinθ	|Fobs.|
0113	1.16	36.6
0114	1.20	32.1
0115	1.25	47.3
0118	1.45	45.6
0119	1.52	45.1
0121	1.21	36.4
0123	1.25	35.6
0127	1.46	35.0
0131	1.32	36.4
0134	1.39	33.2
0135	1.44	39.4
0136	1.49	102.0
0140	1.40	31.0
0142	1.43	25.2
0144	1.49	63.8
0146	1.58	22.9
0152	1.53	35.7
0153	1.54	19.3

APPENDIX 1.

PREPARATION OF 2:6-DIHYDROXY BENZOIC ACID AND ITS SALTS

Several crystals of the acid were sent to us by Dr. Reid. These crystals when mounted about the needle axis gave powder photographs which suggested that crystals of the anhydrous acid might have become coated with a powdery layer of hydrate.

Sodium γ-resorcylate was sent to us in reasonable quantities and the acid was prepared from it.

(a) 2:6-Dihydroxy Benzoic Acid Monohydrate was formed by treatment of sodium γ-resorcylate with dilute sulphuric acid.

(b) Anhydrous 2:6-Dihydroxy Benzoic Acid. Heilbron and Bunbury[106] and Beilstein[107] refer to the free acid as containing one molecule of water of crystallisation. Beilstein states however that the acid loses water in vacuo over H_2SO_4, or by drying at 100°C. Accordingly, attempts were made to prepare the anhydrous acid from the hydrate. The acid hydrate was crystallised and, after superficial drying, a small quantity was placed in a vacuum desiccator and left there for one week. After that time the crystals were removed and dissolved in anhydrous redistilled benzene. The azeotropic mixture was distilled off under reduced pressure. The material was recrystallised from anhydrous benzene.

Rotation photographs were taken about the needle axis. The reflections were very weak and the crystals appeared still to be impure.

The material was purified yet again and recrystallised as before. Once again rotation photographs were taken about the needle axis. Only three or four reflections could be observed on the zero and first layer lines indicating an axial length of ~ 3 Å. There was a considerable degree of powdering and, after an attempt had been made to reset the crystal, the resulting photograph showed complete powdering. Repeated attempts were made to obtain reasonable crystals of the anhydrous acid but no improvement couldbe made. It was decided that the anhydrous acid was quite unstable and unsuited to investigation by the methods heretofore employed.

(c) Potassium Salts. Attempts were made to prepare

(i) potassium hydrogen 2:6-dihydroxy benzoate after the method of Farmer.[108] This author prepared potassium hydrogen salicylate by mixing the theoretical proportions of caustic potash and the free acid in alcoholic solution although he was unable to isolate the acid salt from the normal salt. Dr. Speakman was unable to prepare potassium hydrogen salicylate[5] by this method, but succeeded by gently warming excess of potassium carbonate with salicylic acid in a little water. Salicylic acid was first deposited and later the acid salt crystallised out.

Many attempts were made to prepare potassium hydrogen 2:6-dihydroxy benzoate by each of these methods. It transpired however that the acid salt would only be prepared with some difficulty if at all whereas the normal salt could be prepared fairly readily: this is probably due to the affinity of the acid for water. Attention was therefore turned to the preparation of the normal salt.

(ii) Potassium 2:6-dihydroxy benzoate. 1 gm. acid + .35 gm. KOH were placed in a small flask and dissolved in ethanol and a few drops of water. The product, recrystallised from ethanol, was in the form of long flat plates. Single crystal rotation photographs, taken about the needle axis of the crystal, revealed an axis identical with the 6.7 $\mathring{A}$ axis of the acid hydrate.

Now, 1 gm. $KHCO_3$ was dissolved in a very small quantity of water sufficient to make a saturated solution. 1.72 gm. of reasonably pure acid crystals were then stirred in and a vigorous reaction took place from which a white amorphous solid was precipitated. The solid recrystallised from water in the form of long colourless needles. pH measurements and gravimetric analysis confirmed this substance as potassium 2:6-dihydroxy benzoate.

(d) Sodium 2:6-Dihydroxy Benzoate. The crude sodium salt was crystallised from water. Rotation photographs about the needle axis revealed an axis of about 6 Å; the photograph showed signs that the crystal might be disentegrating and further photographs showed degrees of powdering from slight to extensive. This effect must have been due to deliquescence or efflorescence of the salt. The sodium salt was of little interest and no further work was done on it.

(e) Rubidium 2:6-Dihydroxy Benzoate. Considerable difficulty was found in preparing and isolating a rubidium salt isomorphous with the potassium salt used. The mode of preparation was similar to that for the potassium salt and by varying the conditions very slightly it was found that the free acid could be formed and at least three rubidium derivatives. Two of these forms gave needle shaped crystals withaxial lengths of $\sim$6 Å and $\sim$3.8 Å. The salt with an axial length $\sim$6 Å is probably isomorphous with the sodium salt and that with the 3.8 Å axis appeared to be isomorphous with the potassium salt. pH and density determinations and further X-ray photographs established beyond doubt that this salt was the required isomorph.

Single crystal moving film photographs were taken about the short axis using the Multiple Film Method[82] and intensity estimates were made.

The cross section of the crystal used for intensity measurements on the Okl zone was .24 x .17 mm. No correction was made for absorption.

APPENDIX 2

PREPARATION OF SCATTERING CURVES

Method 1.

The data given by McWeeny[91] for carbon and oxygen were used. An approximate scattering curve for oxygen was calculated from the equation given by McWeeny

$$\bar{f}_O = {}^1/_3 \ (f_O'' + 2f_O^{\perp})$$

where f'' and $f^{\perp}$ are the two principal atomic scattering factors, and a composite scattering factor for carbon and oxygen, f_{CO} was derived

$$f_{CO} = {}^4/_8 \ \bar{f}_O + {}^7/_6 \ f_C$$

(the molecule contains four oxygen atoms and seven carbon atoms).

This scattering curve was put on to a unitary scale and modified by a temperature factor B

$$f' = f_T \exp - B(\sin\theta/\lambda)^2$$

f_T = theoretical scattering factor on unitary scale and f' = effective unitary scattering factor.

$$(F_{obs} - F_K) = m\,G\,f'$$

F_{obs} is the scaled observed structure factor, F_K is the calculated potassium contribution to the structure factor, $m\,G$ is the sum of the atomic contributions for carbon and oxygen (appropriately weighted to allow for the unitary scattering factor).

$$(F_{obs} - F_K) \ / \ mG\ f_T = \exp - B(\sin\theta/\lambda)^2$$

$$\therefore \ \log \ \sum (F_{obs} - F_K) \ / \sum mG\ f_T = (-B/2.303)\ (\sin\theta/\lambda)^2$$

The $(F_{obs} - F_K)$s were divided into .1 ranges of d^* and

$$\sum (F_{obs} - F_K) / \sum m G f_T$$

was calculated for each.

$$\text{Log} \quad - \sum (F_{obs} - F_K) / \sum m G f_T$$

was plotted agains $\sin\theta^2/\lambda^2$ and the best approximation to a straight line was drawn. The temperature factor calculated from the gradient was $B = 3.017$. The straight line drawn through the points did not go through the origin. This indicated a discrepancy in the scaling factor which matters in the presence of another atom, i.e.

$$f' = f_T \exp(-Bd^{*2} - c)$$

where c is a constant and in this case = .87.
As the potassium scattering curve appeared rather sharp for low order planes it seemed likely that it might be scaled too low and it was accordingly modified by the factor $1/.87 = 1.149$. The scattering factors f' and f_T for carbon-oxygen, along with the derived scattering factors for potassium are listed in Table VIII lines 6, 7 and 8.

Method 2.

The scattering factors used were empirical ones for carbon, oxygen and potassium, used in the solution of the structure of potassium hydrogen bisphenyl acetate[2], and derived from the James and Brindley data[89]. (Table VIII, lines 4, 3 and 1).

$$F_{calc} = 2f_K G_K + 2f_O G_O + 2f_C G_C$$

(F_{calc} is the calculated structure factor, f_K, f_O, and f_C are the scattering factors for potassium, oxygen and carbon respectively and G_K, G_O and G_C are the corresponding geometrical structure factors).

Ideally F_{calc} should equal F_{obs} (F_{obs} is the scaled observed structure factor)

$$\therefore \quad 2A f_K G_K + 2B f_O G_O + 2C f_C G_C = F_{obs}$$

The structure factor equations were listed for all planes over .2 ranges of ξ ; then each digit was multiplied by the coefficient of A to give an equation 1), by the coefficient of B to give an equation 2) and by the coefficient of C to give an equation 3). For each particular range of ξ values all the equations 1), 2) and 3) were summed to give three new equations which could be solved for A, B and C. Thus, each atom scattering curve was considered separately. The factors A, B and C of course varied for the different sections of the curves; some variation would be expected as we are not considering an exponential function, and the best approximation to the calculated factors was taken in order to give reasonably smooth curves.

The scattering factors derived by this method are listed in Table VIII, lines 9, 10 and 11.

Method 3.

Completely new scattering curves were prepared using the data given by Berghuis et.al.,[96] (Table VIII, lines 12, 13 and 14) and an overall temperature factor, B and scaling factor, ϕ, were calculated as follows. The method is similar to method 1 except that individual scattering curves were used for all three atoms and these were not put

on to a unitary scale, so that the geometrical structure factors calculated after the Booth synthesis could be used without being weighted.

The reflections were divided into ranges of ξ^2, 0 - .25, .26 - .50 .51 - .75 etc., and over each range F_{obs} and F_{calc} were summed in order to find the ratio which should be plotted against ξ^2,

$$\log \Sigma F_{obs} / \Sigma Gf_T = (-B/2.303) (\sin\theta/\lambda)^2 - c$$

(F_{obs} is the scaled observed structure factor, f_T is the theoretical scattering factor and G is the geometrical structure factor).

$$B = 2.4 \quad \text{and} \quad c = .5$$

The temperature factors for the individual scattering curves were then considered as described in the text.

The final temperature factors for potassium, oxygen and carbon are 3.0, 2.4 and 3.0 respectively and the final scattering factors are given in Table VIII, lines 15, 16 and 17.

Estimation of Temperature Factors inherent in Empirical Scattering Factors.

The empirical scattering factors listed in Table VIII, lines 9, 10 and 11, were considered in relation to the theoretical scattering factors of Berghuis et.al.,[96] Table VIII, lines 12, 13 and 14 and the temperature factors, B, at particular values of ξ were calculated according to the equation

$$B = (\log_{10} f_T - \log_{10} f') \, 2.303/(\sin\theta/\lambda)^2$$

$$= 2.303 \, (\log f_T/f') \, (\lambda/\sin\theta)^2$$

(f_T is the theoretical Berghuis scattering factor and f' is the empirical scattering factor).

The values of B for each atom at different ξ values are given below.

TABLE VII

TEMPERATURE FACTORS.

ζ	.308	.462	.616	.771	.925	1.080	1.230	1.542	1.850
B_K	22.0	12.80	8.74	6.24	5.09	4.41	4.29	4.82	4.12
B_O		9.34	5.90	6.08	5.70	5.14	4.18	2.46	1.58
B_C		16.35	12.11	9.80	8.29	6.58	6.04	3.64	2.55

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TABLE VIII - SCATTERING FACTORS

		0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	
1.	K^+		16.90	15.60	14.10	12.60	11.10	9.75	8.60	7.50	6.60	6.00	5.40	5.00	4.60	4.40	4.16	3.90	3.65	3.40	3.30		original
2.	Rb^+		33.00	31.80	28.70	25.90	23.30	21.00	18.60	16.70	15.00	13.70	12.55	11.60	10.40	10.09	9.85	9.40	8.85	8.50			empirical
3.	O	8.50	8.35	8.00	7.25	6.40	5.70	5.00	4.30	3.60	3.00	2.50	2.10	1.75	1.40	1.20	1.00	0.90	0.85	0.80	0.80		scattering
4.	C	6.00	5.70	5.15	4.40	3.80	3.20	2.60	2.20	1.80	1.60	1.30	1.20	1.05	0.90	0.80	0.70	0.65	0.60	0.55	0.50		factors
5.	K^+		16.90	15.60	14.10	12.60	11.10	9.75	8.60	7.50	6.60	6.00	5.20	4.50	3.90	3.30	2.70	2.40					
6.	CO_T	1.000	0.987	0.950	0.890	0.824	0.744	0.665	0.590	0.520	0.468	0.422	0.380	0.350	0.324	0.300	0.280	0.265	0.255	0.244	0.233		based on McWeeny
7.	CO^I	1.000	0.981	0.934	0.863	0.779	0.685	0.600	0.506	0.426	0.361	0.302	0.255	0.215	0.183	0.160	0.138	0.120	0.103	0.900	0.750	0.610	data[91] Method I
8.	K^+			17.80	16.20	14.40	12.80	11.30	9.90	8.75	7.80	6.85	5.90	5.10	4.45	3.75	3.10	2.70					
9.	K^+			14.80	13.50	12.10	10.95	9.85	8.90	8.05	7.15	6.33	5.55	4.80	4.03	3.25	2.60	2.07	1.82	1.70	1.60		based on empirical
10.	O			7.40	6.93	6.35	5.65	5.00	4.35	3.70	3.10	2.55	2.13	1.80	1.58	1.41	1.35	1.25	1.20	1.18	1.12	1.10	scattering factors
11.	C			4.75	4.15	3.40	2.80	2.28	1.85	1.54	1.26	1.06	0.90	0.80	0.71	0.70	0.69	0.67	0.63	0.62	0.61	0.60	Method 2.
12.	K^+	18.00	17.85	17.45	16.78	15.88	14.96	14.00	13.00	12.05	11.20	10.48	9.80	9.23	8.72	8.31	8.00	7.70	7.40	7.23	7.00	6.80	
13.	O	8.00	7.93	7.60	7.26	6.80	6.30	5.75	5.20	4.70	4.20	3.80	3.40	3.10	2.85	2.62	2.43	2.28	2.11	1.99	1.90	1.80	Berghuis[96]
14.	C	6.00	5.90	5.58	5.20	4.70	4.20	3.70	3.30	2.90	2.60	2.37	2.20	2.05	1.93	1.82	1.75	1.70	1.63	1.55	1.50	1.40	data
15.	K^+	18.00	17.80	17.20	16.25	15.05	14.70	12.40	11.00	9.73	8.60	7.53	6.62	5.81	5.09	4.46	3.91	3.42	3.00	2.60	2.20	1.80	final
16.	O	8.00	7.90	7.60	7.12	6.55	5.86	5.24	4.61	4.00	3.41	2.91	2.50	2.18	1.90	1.63	1.40	1.20	1.05	0.91	0.79	0.68	scattering
17.	C	6.00	5.89	5.55	5.02	4.45	3.82	3.29	2.80	2.35	2.00	1.71	1.50	1.32	1.20	1.00	0.89	0.80	0.71	0.65			factors

APPENDIX 3

WEIGHTED Okl SECTION OF RECIPROCAL LATTICE

In the analysis of the structure the Fourier transform method was not attempted for several reasons. These were 1) that the molecule does not have a centre of symmetry so that the evaluation of the transform would involve calculation of real and imaginary parts and their subsequent combination; 2) that there are four molecules in the unit cell with different orientations so that the separate molecular transforms must be combined; 3) that in any case the contributions from atoms of widely different atomic weights seemed likely to confuse the issue and the effort might be fruitless.

After the structure had been determined however projection down the a axis showed some interesting features which might show up on a weighted reciprocal lattice: these are obvious on figs XIa and XIIa, viz., the centred hexagonal arrangement of molecules to form a "condensed" system and, less obvious, the arrangement of potassium ions in elongated hexagons, each potassium ion being surrounded by a circle of three oxygen atoms.

Accordingly a weighted reciprocal lattice was prepared. The lattice was drawn out in $^{1}/_{d}$ units: the structure factors were put on a unitary scale and divided into groups, each group being represented on the lattice by a black spot of radius proportional to the structure amplitude (more correctly, this should be area).

This lattice is shown in fig. XIII; the majority of the intensities must be attributed to K-O and O-O distances but it is interesting to note that other features can be distinguished. The circle of peaks near to the origin with small reciprocal spacing corresponds to the large rings of molecules and immediately beyond the circle as indicated on the reciprocal lattice diagram is a series of peaks

corresponding to the hexagonally arranged potassium atoms. As one would expect, the centro-symmetrical portion of the molecule has the dominating influence on the transform and the twelve sets of peaks near to the circle of radius .8 Å^{-1} are the most obvious feature. These correspond to the two different orientations of the benzene ring within the anion; these are approximately drawn in.

This small section of work has played no part in the solution of the structure and has only been included for interest.

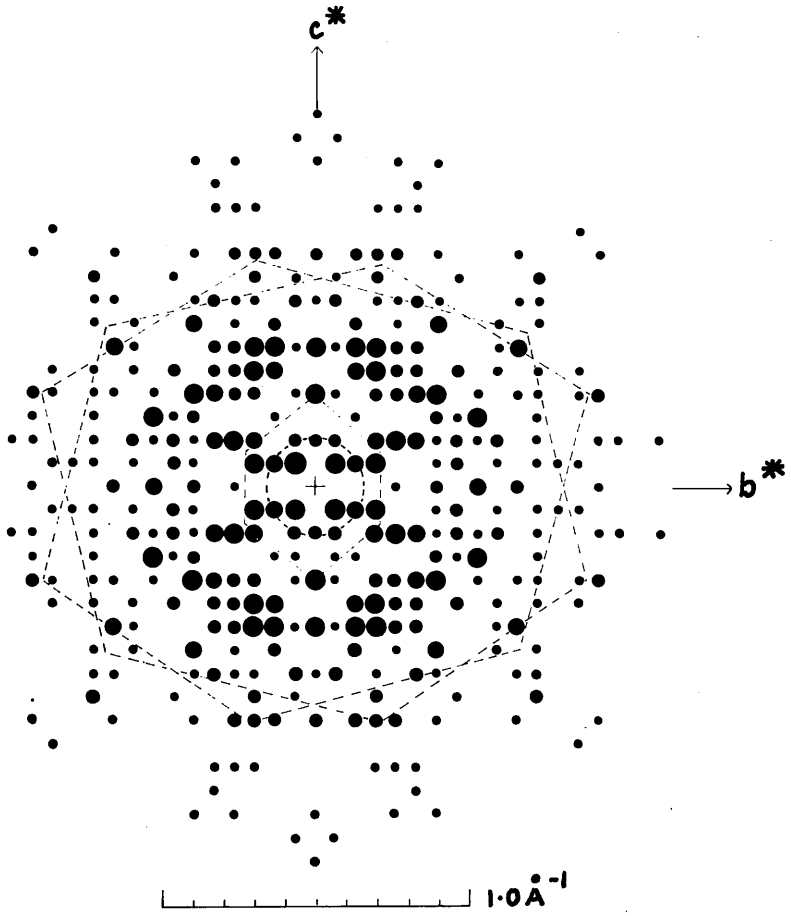

Fig. XIII

b^* c^* net of weighted reciprocal lattice

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